

LABORATORY STUDIES OF
AIDED BLIND MOBILITY.

A thesis presented for the degree of
Doctor of Philosophy in Electrical Engineering
in the University of Canterbury.

by

J.A. Brabyn B.E. (Hons)

1978

ABSTRACT

HN
1758
B795
1978

A review is given of theories of blind mobility, and of efforts to obtain objective data for evaluating sensory aids for the blind. Techniques are developed for making objective measurements of locomotor control performance - an important subset of mobility skills. It is shown that, using mobile subjects performing simple tasks in the controlled environment of a large laboratory, lined to suitable instrumentation, fine distinctions between different levels of performance can be made. A scale of locomotor control performance is developed, comparing a wide range of skill levels between normally sighted and "random" performance (with no auditory or visual feedback). Objective comparisons can be made between various mobility aids within this framework.

Techniques are developed whereby mobility aids using auditory or tactile displays can be simulated in real time using mobile subjects - a long - standing research goal in blind mobility. The performance evaluation techniques can be applied to the simulated aids, allowing investigation of the effects on performance of adjustments in aid cue parameters.

By viewing the mobile human as a control system performing well-defined tasks, objective data can be obtained to supplement the more subjective judgements made in the outside environment, and a deeper insight into the problems of blind mobility is made possible.

ACKNOWLEDGEMENTS.

I am deeply indebted to my supervisors, Professor L. Kay and Dr. H.R. Sirisena for their guidance, encouragement, and many useful discussions during the course of this project. I also wish to thank Dr. E.R. Strelow, without whom much of the work would not have been undertaken.

I am grateful to the staff of the Electrical Engineering Department for discussions and assistance. In particular I am indebted to Mr. W.K. Kennedy for his valuable help.

The financial support of the University Grants Committee is gratefully acknowledged.

Finally, I wish to thank my family and my fiancée, Gillian, for their patience, encouragement, and practical assistance.

CONTENTS,

	<u>Page</u>
Abstract	(i)
Acknowledgements	(ii)
Chapter 1: BRIEF INTRODUCTION	
1.1 The Problem of Blind Mobility	1
1.2 Progress to Date on Sensory Aids for Mobility	2
1.3 Remaining Problems	4
1.4 Contribution of this Thesis	4
References	5
Chapter 2: THEORIES OF MOBILITY AND EVALUATION	
2.1 Introduction	6
2.2 Theories of Mobility	6
2.3 The Evaluation Problem	12
2.3:1 Introduction	12
2.3:2 Sonic Torch Evaluation	13
2.3:3 Pathsounder Evaluation	16
2.3:4 Sonic Glasses Evaluation	16
2.3:5 Nottingham Obstacle Detector Evaluation	19
2.3:6 Laser Cane Evaluation	19
2.3:7 Tactile Imaging Systems Evaluation	20

2.3:8 Summary	20
2.4 Deductions from Previous Evaluation Attempts	21
2.5 Mobility as a Control Problem	22
References	27

Chapter 3: A FIRST STEP: COMPUTER SIM-
ULATION OF ENVIRONMENT AND
DISPLAY.

3.1 Introduction	30
3.2 Limitations of Simulation TEchniques	30
3.3 A Concrete Proposal	31
3.4 System Concept	32
3.5 Description	33
3.6 Choice of Display	36
3.7 Choice of Task and Experimental Procedure	40
3.8 Performance Measurement	42
3.9 Results	43
3.9:1 System Trials and Validation	43
3.9:2 Further Development of Perform- ance Indices	47
3.9:3 Comparison of Steering Wheel and Chair Apparatus	49
3.10 Discussion	51
References	54

Chapter 4: A SECOND STEP: MONITORING
 HUMAN LOCOMOTOR PERFORMANCE.

4.1	Introduction	55
4.2	Instrumentation System Design	56
	4.2:1 Specifications	56
	4.2:2 Possible Configurations	56
4.3	System Description	58
	4.3:1 Mechanical Sensors	58
	4.3:2 Tensioning Method	59
	4.3:3 Line Length Monitoring	61
	4.3:4 Solving for Position	64
4.4	System Accuracy	66
4.5	Software	69
4.6	Development of Performance Indices	71
	4.6:1 Path Plots	71
	4.6:2 Distance and Speed Graphs	74
	4.6:3 Speed - Derived Performance	
	Indices	80
	4.6:4 Path Deviation Indices	82
	4.6:5 Path Curvature	85
	4.6:6 Gait characteristics versus	
	Path Control	86
	4.6:7 Effects of Monitoring System	
	Errors and Sampling Rate on	
	Performance Indices	88

4.7	Validation of Performance Indices	92
4.7:1	Introduction	92
4.7:2	Demonstrations of Mobility	
	Performance	93
4.7:3	Visual Control Tasks	93
4.7:4	Locomotor Control with Degraded	
	Perceptual Input	97
4.8	Discrimination between Blind (Aided)	
	and Sighted Performance	99
49	General Discussion	101
	References	102

Chapter 5: A THIRD STEP: AID SIMULATION AND EVALUATION WITH REAL LOCOMOTION TASKS

5.1	Introduction	103
5.2	Previous Aid Simulation Proposals	104
5.3	Effects of Possibly Display Parame-	
	ters on Simulation Techniques	105
5.4	System Requirements	107
5.5:1	General	108
5.5:2	Monitoring Subject Orientation	110
5.5:3	Obstacle Search Strategies	112
5.5:4	Analog Computation	116
5.5:5	General Software Considerati-	
	ons	118
5.6	Simulation System Error Analysis	121
5.7	System Evaluation	125

5.7:1 Simulation of Single Object	125
Sensor	
5.7:2 "Sonic Glasses Simulation	
Problem	126
5.7:3 Validation of "Sonic Glasses"	
Simulation	128
5.7:4 Discussion	135
5.8 Conclusions	136
References	137

Chapter 6: EFFECTS OF SIMULATED CUE VARIATIONS ON USER PERFORMANCE

6.1 Introduction	138
6.2 Effects of Range Cue Variation	139
6.2:1 Experimental Conditions	139
6.2:2 Procedure	140
6.2:3 Results	142
6.3 Effects of Direction Cue Variation	144
6.3:1 Experimental Conditions	144
6.3:1 Experimental Procedure	144
6.3:3 Results	145
6.4 Supplementary Data from a Long-Term	
Aid User	147
6.4:1 Introduction	147
6.4:2 Procedure	147
6.4:3 Results	148
6.5 Discussion	152
References	155

Chapter 7: CONTEXT OF PERFORMANCE VARIATIONS

7.1	Introduction	156
7.2	Veering Studies	157
	7.2:1 Introduction	157
	7.2:2	158
	7.2:3 Results	158
7.3	Performance Using "Natural Obstacle Sense"	160
	7.3:1 Introduction	160
	7.3:2 Method	161
	7.3:3 Results	164
7.4	Performance Under Conditions of Restricted Vision	169
	7.4:1 Introduction	169
	7.4:2 Method	170
	7.4:3 Results	172
7.5	Conclusions	174
	References	176

Chapter 8: FURTHER APPLICATIONS OF SIMULATION AND EVALUATION METHODS

8.1	Introduction	177
8.2	Tactile Display Simulation	177
	8.2:1 Introduction	177
	8.2:2 Simulation System Modification	181
	8.2:3 Experimental Testing	183
	8.2:4 Discussion	189

8.3	Effects of Display Sound Externalization	190
8.3:1	Introduction	190
8.3:2	Method	191
8.3:3	Results	192
8.3:4	Supplementary Results	194
8.3:5	Conclusions	195
8.4	A Comparison of Two Existing Devices	195
8.4:1	Introduction	195
8.4:2	The Sonicguide	196
8.4:3	The Single Object Sensor	200
8.4:4	Summary	203
8.5	Other Applications	203
8.5:1	Gait Analysis	203
8.5:2	Effects of Drugs on Walking	
	Performance	207
	References	209

Chapter 9: ADVANCING LOCOMOTOR CONTROL
AND MOBILITY THEORY

9.1	Introduction	212
9.2	A control System Model of Purposeful Locomotion	212
9.2:1	Introduction	212
9.2:2	The Human Operator in a Control Loop	213
9.2:3	Linear and Non-Linear Models	215
9.2:4	Formulation of Model	218
9.2:5	Implications	221

9.3	Laboratory Studies in Context	224
9.3:1	The Relevance of Locomotor Control Studies	224
9.3:2	Relationship between Labor- atory and Field Studies	225
	References	227
Chapter 10: <u>CONCLUSIONS</u>		
10.1	Contribution of this Thesis	228
10.2	Suggestions for Future Research	231
10.3	Overall Conclusions.	232.
Appendix 1:	Training Methods	234
Appendix 2:	Programming for Flexib- ility of Direction Cue Specification	236
Appendix 3:	A Proposal for a Sonar- Driven Tactile Display	238
Appendix 4:	Publications.	240.

CHAPTER 1

BRIEF INTRODUCTION

1.1 THE PROBLEM OF BLIND MOBILITY.

Mobility has been defined by Foulke (1) as "the ability to travel safely, comfortably, gracefully and independently through the environment." It involves a complex set of perceptual and locomotor skills which are as yet poorly understood. More than just the ability to walk, mobility includes orientation and navigation. Rapid and accurate spatial judgements are required, together with the ability to predict one's own travel path and the paths of others.

Severe visual handicaps, reducing the spatial information available to the pedestrian, must, therefore, be expected to impair travel skills. Compensation for this impairment is a most important rehabilitation problem for the blind, since mobility is a vital key to personal independence and vocational success (2).

It has been estimated by the National Centre for Health Statistics (3) that over 0.2% of the United States population is visually handicapped to such an extent as to preclude perception of moving objects - clearly necessary for mobility. Tentative extrapolation of these figures to a world-wide scale suggests that approximately 6 million persons are affected. Considering the magnitude of the problem, the amount of study and research devoted to it has been minimal.

Apart from the speculative accounts by Gibson (4), very little information presently exists on the study of purposeful locomotion.

Until recently, the main thrust of research and development in the field has been the direct application of available technology to the production of devices thought, by their inventors, likely to satisfy wholly or partly the needs of the mobile blind. Perhaps a more logical approach would have been a program of experimental research into mobility itself, attempting to define the problem more satisfactorily before developing engineering solutions.

However, such experimental work is difficult to conceptualize, carry out and evaluate. In the event, the laboratory studies and other investigatory programs have been commenced only after the arrival and partial failure (at least in terms of general acceptance) of the first generation of sensory aids.

1.2 PROGRESS TO DATE ON SENSORY AIDS FOR MOBILITY.

One of the earliest aids for blind mobility, and perhaps still the most successful, was the long cane. Variants of this have probably been used since the earliest times. A refined technique for using this aid was developed by Richard Hoover while working with veterans from World War 2 (5). This allowed detection of obstacles at a range just sufficient to avoid collisions, and provision of information concerning ground texture, gutters and other low-lying obstacles which few electronic aids can detect. For these reasons the long cane, or "typhlocane", has become known as a "primary aid" - satisfying the basic conditions for avoiding physical injury.

The other "primary aid" is the guide dog, which has been a very successful travel aid since the 1930's (6). However, users must be carefully chosen for temperament and compatibility with the dog, and only an estimated 1% of the legally blind population travels by these means, compared with the 30% using canes (7). The guide dog is very expensive

in terms of breeding, training, and maintenance, and by-passes rather than solves the blind person's perceptual problem. The dog provides very little information concerning the spatial characteristics of the environment.

Attempts to supplement spatial information via the blind person's remaining senses using sophisticated electronic sensory aids were stimulated by the knowledge gained during WWII on radar and sonar systems. Subsequently, the commercial introduction of the transistor (circa 1955) facilitated portability of such systems.

Of the better-known inventions in this field, the Kay Sonic Torch reached the working prototype stage by 1962 (8), the Russell Pathsounder by 1965 (9), the C-4 Laser Cane by 1967 (10), and the Binaural Sensory Aid by 1968 (11). Contemporary devices which have achieved less renown include the M.I.T. Inertial Guidance Device, the Jacobson Compass, the N.R.C.C. Radio Compass (12), the Swaile Radio Compass (13), Nelkin's Ultrasonic Guidance System (14), the Electoftalm Mobility Aid (15), Chardin's Mobility Aid (16), and others (17). Most of these had been developed by 1965, and although nearly all were considered by their inventors to be viable sensory devices the majority soon faded into obscurity or were abandoned. By 1969, the rate of appearance of new aids had declined to a comparative trickle. The principal newcomers in the next eight years were the Nottingham Obstacle Detector (18), the Mowat Sensor (19), and the Canterbury Single Object Sensor (20), although long-term research continued on tactile vision substitution systems (21, 22) and cortical implants (23,24). Development also continued on the Russell Pathsounder and the Laser Cane, while the Binaural Sensory Aid achieved commercial production in 1973. None of these three reflected new ideas - all had been invented by 1968.

1.3 REMAINING PROBLEMS.

The literature is littered with accounts of devices that have found only limited experimental use. In general, they have neither gained wide acceptance nor been proven decisively superior to conventional solutions. When the present research commenced, only the "Sonicguide" - a version of the Binaural Sensory Aid - was being produced commercially.

Clearly, to gain acceptance of secondary electronic aids was more difficult than anticipated. Efforts in this direction were handicapped by the fact that it was difficult if not impossible to evaluate mobility aids objectively. It could not, therefore, be proved that any one aid was superior to others, or even that the best gave better results than the traditional "obstacle sense" (25) and long cane. Amid the rival claims of the many sensory aid inventors, what was lacking was a reasoned and objective approach to mobility evaluation. It was clear that a very broad range of possible aids was technically feasible and that engineering expedience should no longer be the overriding consideration in solving the blind mobility problem. It remained to investigate more thoroughly the closely related topics of the mechanism and the evaluation of mobility before it would be possible to optimise the man-machine interface. Acting on the suggestion of Kay, long-term research into this problem was begun, with the ultimate aim of determining optimal characteristics for mobility aids.

1.4 CONTRIBUTION OF THIS THESIS,

This thesis reports on the first stage of the above research, and is an attempt to make some contribution to objectivity in mobility evaluation. According to the criteria developed, performance of electronic aids is compared with normal and restricted

vision, natural obstacle sense and auditory information. Attention is focussed mainly on the locomotor control aspects of mobility - those concerning the control of one's bodily path through the immediate environment - rather than the more global features of navigation and land-mark recognition. This concentration greatly facilitates objectivity, and a rationale for the choice is explained in Chapter 2.

In addition to tackling the evaluation problem, methods are developed whereby mobility aids using simple auditory and tactile displays can be simulated under realistic, dynamic conditions using subjects free to move within a spacious environment containing simple objects. These techniques represent the achievement of a long-standing goal in the mobility field (24, 25, 26), and one which was considered difficult if not impossible to reach when the present research began.

Finally, a simple control system model is proposed for the mobile human, to assist in understanding the mechanism of the perceptual motor system in mobility and how it is influenced by variations in sensory input.

REFERENCES

- (1) Foulke, E.; "The Perceptual Basis for Mobility".
AFB Research Bulletin, 1971, 23, 1 - 8.
- (2) Leonard, A.J.; "Long Cane/Orientation Training for Blind Pedestrians".
Insight, 1969, 4/5.
- (3) National Centre for Health Statistics; "Characteristics of Visually Impaired Persons". U.S. Department of Health, Education, and Welfare, Washington, D.C. 1968.
- (4) Gibson, J.J.; "Visually Controlled Locomotion and Visual Orientation in Animals". Brit. J. Psychol., 1958, 49, 182 - 194.
- (5) Hoover, R.E.; "The Cane as a Travel Aid" N.P.A. Zahl (Ed.) Blindness. Princeton, N.J.: Princeton University Press, 1950, pp 353 - 65.
- (6) Kay, L.; "Non-Visual Perception of Space for the Blind". Transactions Opthal.Soc. N.Z., 1971, 23, pp 17 - 21.
- (7) Organization for Social and Technical Innovation, Inc. "Blindness and Services to the Blind in the United States". Cambridge, Massachusetts: OSTI Press, 1971.
- (8) Kay, L.; "Sonic Aids for the Blind". Mobility of the Blind Association Newsletter, No. 16, July 1972.
- (9) Russell, L.; "Travel Path Sounder". Proc. Rotterdam Mobility Research Conf, May 1965, American Foundation for the Blind, 1965.
- (10) Freiburger, A.M.; "Fabrication of Obstacle Detectors for the Blind". Bulletin of Prosthetics Research, 1967 BPR 10 - 8 .
- (11) Kay, L.; "An Aid to Mobility for the Blind: What Progress in Ten Years? " P.W. Nye (Ed), Proc. Conf. on Evaluation of Mobility Aids for the Blind. Washington, D.C.: National Academy of Engineering, 1971.
- (12) Sensory Aids Evaluation and Development Centre; "Final Report to the Vocational Rehabilitation Administration". Massachusetts Inst. of Technology, 1965.

- (13) Leonard, J.A.; "Modern Trends in Mobility". AFB Research Bulletin, 1969, 19, 73 - 89
- (14) Nelkin, A.; "Ultrasonic Aid for the Blind" Proc. Rotterdam Mobility Research Conference. New York: American Foundation for the Blind, 1965.
- (15) Starkiewica, W., Kuliszewski, I.; "Progress Report on the Electropalm Mobility Aid". Ibid.
- (16) Charden, G.; "A Mobility Aid for the Blind", Ibid.
- (17) Shroger, P., Susskind, C.; "Electronics and the Blind", Advances in Electronics and Electron Physics, 1964, 20, 261 - 301.
- (18) Armstrong, J.; "Summary Report of the Research Programme on Electronic Mobility Aids". Report, Psychology Dept., University of Nottingham, 1973.
- (19) Pressey, N.; "Mowat Sensor", Focus, 1977 11, 3, pp 35 - 39.
- (20) Kay, L., Bui, S.T., Brabyn, J.A., Strelow, E.R.; "Single Object Sensor: A Simplified Binaural Mobility Aid". Journal of Visual Impairment and Blindness, May, 1977, 210-213.
- (21) Collins, C.C., Madey, M.J.; "Tactile Sensory Replacement". Proc. San Diego Biomedical Symposium Vol. 13, February, 1974
- (22) Bliss, J.C., Katcher, M.H., Rogers, C.H., Shepard, R.P.; "Optical-to-Tactile Image Conversion for the Blind". IEEE Trans MMS, 1970 MMS - 11, 1, 58 - 65
- (23) Brindley, G.S., Lewin, W.S.; "The Sensations Produced by Electrical Stimulation of the Cortex". J. Physical., 1968, 196, 479 - 93.
- (24) Schimmel, H., Vaughan, H.G.; "Feasibility of Visual Electro-Cortical Prosthesis". In Sterling et al (Eds.); Visual Prosthesis: the Interdisciplinary Dialogue, New York: Academic Press, 1971.
- (25) Worchel, P., Dallenbach, K.M.; "Facial Vision: Perception of Obstacles by the Deaf - Blind". Am. J. Psychol., 1947, 60, 4, 502 - 553.

CHAPTER 2

THEORIES OF MOBILITY AND EVALUATION

2.1 INTRODUCTION.

The limited acceptance of the first generation of electronic mobility aids led Kay (1) to suggest the need for more basic research into mobility, so that decisions regarding future inventions and modifications could be made more objectively.

A need had arisen for a theory of mobility (1,2), together with objective means for evaluating mobility performance (3,4). The latter was clearly desirable in the process of deciding which, if any, of a number of available aids was superior to the others, and in measuring progress towards the goal of "performance similar to sighted" (5). The desirability of a theory of mobility was not as obvious, but was considered to be helpful for better understanding and definition of the mobility problem.

The present chapter begins with a review of the attempts so far made to formulate such a theory. This leads logically to a discussion of mobility evaluation. Arguments are presented for attempting the development of evaluation techniques based on locomotor control skill. This is an important subset of mobility skills which should be objectively measurable in the controlled environment of a suitable laboratory.

2.2 THEORIES OF MOBILITY.

Perhaps the most notable attempts to date at formulating a basis for blind mobility studies have been those of Leonard (1968), Foulke (1971) and Kay (1974) (5,6,1).

Leonard's stated purpose in advancing his theory was to "clarify and consolidate contemporary ideas about mobility of the blind". He advanced an "agreed aim" (that of enabling the blind to achieve the same degree of independent mobility as that enjoyed by the sighted), compiled a check-list of "requirements" (motivation, obstacle detection, navigation, etc.) and available "resources" (memory, touch, canes, electronic aids, etc.) for mobility. He also voiced some speculation on future developments. The need was recognized for some standards for comparison by which to determine the extent to which the "agreed aim" had been reached. With this in mind, he put forward a rating scale for blind mobility which is discussed below in section 2.3. He also expressed the need for more efficient assessment of the blind for training purposes, a common language to describe routes and a common system for making tactile maps.

As a summary of the known facts in 1968, the theory succeeded in its aim. Particularly useful in this context was the requirements-resources table. Amongst its suggestions for solving the problems of blind travellers are the use of some form of "straight-line indicator" to assist straight line travel by the blind, and the requirement for some means of assessing mobility performance. The former suggestion highlighted the importance of locomotor control - i.e. control over bodily path - as a factor in mobility, to be considered alongside landmark identification and navigation skills. The point regarding mobility assessment was to become a common theme.

In a paper entitled "The Perceptual Basis for Blind Mobility" (6), Foulke states the need for a Theory of Mobility "to guide us in the refinement of training methods and the design of information-gathering instruments designed to assist mobility". He too acknowledged the need to "learn how to measure significant aspects of total mobility performance, in order to gauge the contribution of a wide variety of

factors to that performance". Although the latter problem is not tackled, the discussion of the mobility problem is impressive. Mobility is analysed as a series of "decisions" all leading towards some "objective". The principal idea contained in the theory is that of a "schema" - an abstract conglomeration of information about the course followed - which is synthesized by the pedestrian and stored in his brain. Once the schema is organised, the subject can base his behaviour on it, and need sample his environment only from time to time for the feedback information needed to keep him on course - that is, to "keep the schema in proper registration with the terrain it represents". The schema may take several traverses of the course to build up. The feedback information obtained by the sampling process may indicate that the schema is in or out of registration - that is, on or off course. If he is off course he must have a schema including some of the surrounding environment so that a departure from the path will not place him in a novel situation where none of the stimulation he can experience is meaningful. There is thus a heavy emphasis on learning from practice. However, "environmental redundancy" - the tendency of the environment to be ordered rather than totally random - materially assists this process.

After discussing the risk factors involved in making the course modifying decisions, the theory moves on to an appraisal of electronic aids, and the distinction is made between a "clear-path indicator" and an "environmental sensor". The former is simply an aid which detects the presence or absence of an obstacle in front of the user, while the environmental sensor gives more information about a larger section of the surrounding environment. In practice the two overlap, because of environmental structure and the fact that a clear path indicator can be scanned to survey the environment. It is postulated that "the ideal environmental sensor would be one with a display so informative

that its user could successfully negotiate a novel terrain on the basis of contemporaneous information. The visual system is such a sensor. Several interesting questions are then asked regarding the differences between blind and sighted mobility, although these are not framed in a manner which suggests readily tested hypotheses.

In sum, Foulke's theory gives insight into the blind pedestrian's problem, and makes a serious attempt to define an ideal mobility aid.

More recently Kay (1) suggested that any mobility theory must be "in a form which can be used quantitatively to evaluate progress toward greater mobility for blind persons".

The theory itself takes the form of 9 "laws", which, when satisfied, will "enable a traveller to move from place to place with safety, ease, and grace". The laws are : (pp 49-51)

1. The traveller must possess the ability to propel himself safely over the terrain to be travelled at a normal walking pace.
2. The traveller must be able to control the movement of his body.
3. The traveller must have the ability to guide his body parallel to a boundary at a normal walking pace.
4. The traveller must be able to direct the movement of his body towards a specific thing, and, if required, touch it, with full control of this action.
5. He must be able to negotiate round an object and re-establish the desired course at a normal walking pace.
6. He must understand the laws of environmental structure (environmental grammar).
7. He must recognize spatial patterns forming sections of the physical environment (words and sentences of the environmental

language).

8. He must recognize sections of the environment as a part of the world and piece these together to form a suitable route (environmental text).
9. He must be able to store a cognitive map of the desired route and position himself on this map during the journey (remember the essential meaning of the text and be able to recall the main parts of this.)

Most of these statements seem reasonable at first sight, and certainly they have so far proven uncontroversial.

Considering the theory point by point, it is evident that laws 1 and 2 fall into the realm of physiotherapy and are included mainly for completeness. Laws 3 - 5 are of most interest to the sensory aid researcher or mobility instructor, and are perhaps most capable of "quantitative evaluation", although no means for this is suggested. Laws 6 - 9 fall more into the category of helpful speculation. The idea of an environmental grammar and language, also put forward by Clowes (1965) (5), appears to be a useful one in understanding mobility, and these last laws resemble Foulke's "schema" concept. Although laws 6 - 9 may be the most useful of all in helping to understand the global aspects of mobility, they are in a form which makes them difficult to prove or disprove, and are unfortunately the part of the theory least suitable for objective evaluation.

Other attempts at theories of mobility have included that by Krigman (7) who proposed a simple mathematical model of mobility representing the human as an information "gathering", "using", and "losing" system. The model results in a very simple equation expressing velocity in terms of probe range and sweep rate, while factors

such as reaction time and stopping distance are neglected for simplicity. A number of experiments follow which apparently verify one prediction from the model (that velocity is independent of path complexity). The experiments do not support other predictions from the model, namely, the relations between probe range and velocity and between orientation-memory decay and velocity.

The speculative accounts of Gibson (8,9) concerning the role of vision in locomotion emphasise the importance of the visual flow pattern and the centre of expansion. He postulated that maintaining coincidence between one's aiming point and the focus of expansion is the primary means for controlling locomotion, and that the optical flow pattern is the source of all information for controlling locomotion relative to the environment. These ideas have been expressed in mathematical form (10) and have been used in explaining control of automobiles and aircraft by human operators. The importance of the focus of expansion has been questioned by Johnson, White, and Cumming (11), who measured large errors in estimation of its position. However, the concept of an outward moving flow pattern has influenced the design of certain tactile and auditory displays (12), especially those intended to be "environmental sensors" rather than "obstacle detectors".

In summarising the theories of mobility advanced in the literature, it can be said that they give an insight into the problems of the mobile blind, but are of indirect assistance only in solving those problems. Nearly all authors agree that little progress can be made without improved means of evaluation for sensory aids, and this is acknowledged as a major problem confronting the field. Without means of evaluating mobility, a Theory of Mobility loses much of its impact since testing its validity is almost impossible.

2.3 THE EVALUATION PROBLEM.

2.3:1 Introduction

Many methods have been put forward in the literature for evaluating mobility and mobility aids, usually more subjective than objective. The problem is complex, since there are many factors to consider. These include the purely cosmetic and physical aspects of the device itself - how small it is, how inconvenient, how reliable, and how comfortable. But perhaps the ultimate test of an aid is its degree of acceptance by the blind community.

Granted that certain physical requirements are met, attention must centre on the variables which are directly concerned in mobility - orientation, navigation, perception, confidence, safety, stress, and many others.

A rating scale developed by Wright was put forward by Leonard (5) in 1968 as a starting point for mobility evaluation. This classed blind travellers on a scale from 1 to 10 according to their travel habits - for example whether they used the cane, the guide dog, or neither. The highest rating was given to those who "travel in familiar and unfamiliar environments without assistance". This type of scale might be useful after a long period of aid use by many people, but unfortunately offers little for those who may wish to evaluate changes in existing aids or assess the value of a new device. No objective means of establishing the position of a new device within such a rating scale was suggested.

Most other evaluative procedures have centred around specific devices, and typical examples of these are summarized below.

2.3:2 Sonic Torch Evaluation

The first electronic mobility aid to receive widespread attention was the Sonic Torch (13), also known as the Kay Sonic Aid, the Ultra Electronics Sonic Mobility Aid, or simply the Sonic Aid. This was a narrow beam, wide-band F.M. system with an auditory display relatively rich in information. The device was hand-held, and was used in lieu of the long cane as a primary aid. It was first evaluated by Leonard and Carpenter (14) in 1962 using the first 10 prototypes. Although this report was unable to show that using the device helped mobility as such, batches of 100 and 1000 aids were subsequently produced and were the subject of many evaluation reports.

A major evaluation was carried out at St. Dunstan's (14,15), using 23 subjects. Much of the testing was concerned with accuracy of pitch (and therefore range) estimation under various conditions. Target recognition skills were also tested, using recordings of device sounds taken when the stationary torch was pointed at different surfaces. Scores were allocated according to the number of correct responses by a subject. Unfortunately these tests were related indirectly at best to the real mobility situation, and were not in a form which could be generalised to other types of aid (such as simple obstacle detectors). Closer to this ideal was the measurement of average speed and percentages of obstacles avoided in an artificial "avenue" with a handrail down one side. The results showed that the average rate of advance of subjects using the device was only one-third of their speed using a long cane. This slowness was "not accompanied by striking success" in detecting objects in or alongside the path. Remarks concerning the final street work were mainly qualitative, apart from the observation that rates of advance were halved compared with the subjects' normal performance with cane or guide dog. In measuring performance

under dynamic conditions, it was concluded that "defining errors is difficult enough, measuring them is worse". Difficulties due to the short periods of training and practice were encountered in this evaluation, and the authors were unable to give any definite assessment of the aid's value.

A further evaluation using 17 subjects was reported by Cranmer (17), whose reaction was generally more favourable. One subject was reported to have his lifestyle changed by the device, which enabled him to travel for the first time without a sighted guide. The ability of subjects to detect and recognize different objects was noted, together with the freedom subjects felt from the concern of colliding with other pedestrians. However, no data was presented to confirm the report's conclusions.

An evaluation by Riley, Weil, and Cohen (18) with 19 subjects used pitch recognition tests and also a circular obstacle course 150 feet in length. The latter represented a serious effort to measure performance in a controlled manner. The course, which had been used in 1962 for cane mobility research, contained an arbitrary arrangement of steps up and down, with obstacles in or alongside the path. The validity of such a course in testing a device such as the Sonic Torch, which was ill-suited to the detection of uncued steps, is debatable. In the real environment, steps in the terrain are often predictable from other cues such as poles and doorways which the Torch could detect adequately. However, the evaluation did attempt to achieve some objectivity, performance being measured in terms of rate of advance and numbers of "harm events". The results showed a halving of speed and a large increase in "harm events" when the Sonic Torch was used. "Harm events" were ill defined, but generally a decline

in performance was indicated. Personality tests showed that success with the aid was correlated negatively with "defensive inflexibility", and it was concluded that more emphasis should be placed on selecting suitable subjects and in improving training.

Sharpe (19) evaluated the capabilities of the Sonic Torch as taught by the St. Dunstan's Instruction Manual (20). Four sighted subjects under blindfold were used, and the principal method of scoring was the time taken to achieve proficiency in given tasks. In addition, an attempt was made at scoring individual lessons but as this became more difficult and subjective in later lessons (for example, shore-lining), these data were not presented. Self-rated anxiety levels were noted, and a final assessment was made in terms of proficiency in identifying objects and in "clear path/shoreline following" over two street routes. The latter was scored by timing and noting "error rates". The results showed, in contradiction to earlier reports, that the trainees were faster than cane users travelling over the same course, and were "very competent" at obstacle detection and avoidance. Unfortunately, scoring of "errors" was not in a form suitable for direct comparisons, while the difficulties of determining whether an error had occurred were noted. The overall conclusion, however, was that the Sonic Aid was suitable as a primary aid, comparable in terms of speed and efficiency with the long cane.

In general, the various evaluation efforts related to the Sonic Torch had several unsatisfactory features. The subjectively-based criteria used by most produced disagreement as to whether or not any improvements or disruptions of mobility skills occurred. Very little constructive criticism was offered, no satisfactory basis for assessment was agreed upon, and few reports drew any firm conclusions.

These features proved to be common to a large section of the subsequent evaluations carried out on other electronic aids.

2.3:3 Pathsounder Evaluation

The Lindsay Russell Pathsounder was the subject of further aid evaluations. This device is an ultrasonic, chest-worn obstacle detector with a range of 6 feet. A report by Russell (21) mentioned collision data from one subject which showed a marked reduction in collisions and a slight reduction in speed when the device was used. Progress of another subject was reported by Curtis (22), who considered the device to be a useful aid for mobility, although evidence was only anecdotal.

2.3:4 Sonic Glasses Evaluation

The next major series of evaluations was associated with the introduction of the Binaural Sensory Aid, or "Sonic Glasses" (23) in 1970-72. This device is a binaural head-mounted version of the sonic torch concept, providing "stereophonic" direction information within a wide ($60^{\circ}+$) beam, together with range and surface texture information similar to the Sonic Torch. Users of the Sonic Glasses in the street environment were expected to use a long cane for detection of steps and low obstacles.

A major international effort was mounted to evaluate this device comprehensively. Two hundred trainees and twenty trainers were involved. An attempt was made at Boston College in April/May 1971 to design a truly rigorous evaluation based on objective performance measures. It soon became evident, however, that most instructors felt that mobility was "too complex to measure at present", and the measures used in the past were "too inadequate to be of real value" (24). It was, however, agreed that "Score Sheet I" would be used,

recording the time taken for each subject to reach "satisfactory" performance of Controlled Environment tasks. These tasks are described in more detail in section 2.4 below, but were designed for training and testing subjects' skills in orientation and locomotor control using a controlled environment consisting of arrangement of poles. Apart from the Score Sheet, it was agreed that experienced observation of mobility performance by some 30 instructors involved would give the most reliable possible assessment of the capability of the man/machine system. This conclusion was surprising in view of the divergence in opinion resulting from the earlier Sonic Torch evaluations. The decision was not due to any distaste for objective means of evaluation, but simply to the fact that the means were not available. It was decided to film performance wherever possible to supply some type of recorded data.

In the event, even Score Sheet I was not used by most evaluation teams (24,25), and little or no objective data arose from the study. This resulted in a diverse series of reports being produced, with individual authors choosing different evaluation techniques. However, after the completion of the training programs, a questionnaire, designed by Airasian (26) to test user opinion, was widely circulated. This revealed a generally positive attitude towards the aid by trainers and trainees. 95% of instructors wished to continue training, and most trainees considered their mobility to have improved through using the aid, although independent travel time was not increased.

The formal evaluation reports were generally similar to those produced for the Sonic Torch. The report of the Arkansas group (27), for example, disclosed that although most subjects reported a reduction in travel stress using the aid, the mobility tests resulted in slightly

poorer performance with the aid than without, (measured in terms of "number of missed cues"), although the difference was not statistically significant. The report on the Illinois evaluation (28) suggested that travel tension rose rather than fell for subjects using the device. A street walk over a standard course was scored in the usual way (recording harm events, veering, missed cues, etc). Results were inconclusive - characteristic of this technique, which unfortunately involves difficult subjective decisions.

Thornton's report (29) on the British evaluation effort was much more positive in tone but was not supported by any data. There was majority agreement on reduction of travel stress and better orientation facility, while a recurring criticism (in reports of both Sonic Torch and Sonic Glasses evaluations) was the poor standard of device reliability.

A serious attempt at objective evaluation was represented by a report from Nottingham (30). This reflected the efforts of Armstrong and Leonard (31, 32, 33, 34) to render assessment of mobility over a standard street route more objective. The resulting techniques entailed a division of mobility into safety, efficiency, and stress. Safety was measured according to the frequency of bodily contacts with the environment, accidental departures from the pavement, and detection of down kerbs. Efficiency was measured using factors such as average walking speed, cane contacts with inner and outer shorelines (measuring ability to maintain a straight course), cane contacts with obstacles, and the "productive walking index", (or proportion of elapsed time spent in actual locomotion). Average stride length was used as a measure of stress. The techniques were later extended (34,35) to include frame by frame film analysis for estimation of veering characteristics.

Two groups of subjects - 2 relatively inexperienced and 3 more experienced users - were evaluated with and without the Sonic Glasses. Although some measures (e.g. stress and number of cane shoreline contacts) showed insignificant changes between the two conditions, and others did not all favour the same condition, both groups of subjects were judged to exhibit overall improvements in performance when using the aid.

2.3:5 Nottingham Obstacle Detector Evaluation

These techniques were also used to evaluate the Nottingham Obstacle Detector (36), which has a range of 7.5 feet and six discrete range resolution elements. The reports concluded that statistical analysis of results suggested no improvement in mobility performance for subjects using the aid, although visual inspection of the data appeared to show improvement in some areas - for example the device did detect obstacles straight ahead of the user.

2.3:6 Laser Cane Evaluation

A major mobility evaluation study (37) was carried out in 1972 to assess the Bionic Laser Cane, a device of long-cane shape with three laser beams pointing ahead for obstacle detection. An attempt at objective data analysis was made by recording "critical events" - such as body contacts, hesitations, orientation errors, and others. In line with similar reports on other devices, it was found that the data were "insufficiently reliable to allow firm conclusions". Even when the data were supplemented by questionnaires, only a "marginal" improvement in mobility could be attributed to the aid.

A Swedish version of the Laser Cane, using only one laser beam, was the subject of recent evaluations (1975-1977) by Jansson (38,39).

These were systematic studies under controlled conditions, using 3-6 subjects. Subjects were asked to stop when an obstacle was detected in the travel path, and the proportion of successful detections, and stopping distance, were used as dependent variables. The studies showed that one cane with a crook gave a larger proportion of detections than another without a crook, and that increasing the range of the laser increased both reliability of detection and stopping distance. Dependence of detection on the scanning pattern used was also established. These experiments, although limited to obstacle avoidance, represented a systematic approach to the problem and were in a form suitable for suggesting improvements to the aid.

2.4:7 Tactile Imaging Systems Evaluation

Although tactile imaging devices are still in the experimental stage, Collins, Scadden, and Alden (40) applied Armstrong's mobility evaluation techniques to such a device in 1977. An indoor environment cluttered with furniture was used, and the experiments showed a steady increase in "productive walking index" and obstacle avoidance as practice advanced, while average speed rose to 1 foot per second. An experiment in which subjects were asked to approach and point to an object, while elapsed time and pointing error were measured, was reported by Jansson (41). Although results were considered satisfactory, it was found that presence of masking targets and use of a wide camera angle upset performances, suggesting difficulties might be encountered in outdoor mobility.

4.3:8 Summary

Of the methods used in the past to evaluate mobility aids, only a minority have been objective. The techniques of Armstrong and Jansson appear to be most advanced in this direction. The latter has

been the only method adaptable to suggesting improvements to existing devices, and even this dealt only with simple obstacle detection.

In the evaluative procedures used by the majority of researchers, many of the measures used are subjective, while many (such as frequency of cane contacts with shoreline) depend heavily on individual primary aid technique. Usually, the environment is not controlled and each experimental trial is really a different experiment - due to variable conditions of traffic (vehicular and pedestrian), weather, and physical characteristics of the environment. Few if any of the evaluations reported to date have given definite conclusions of any kind, and none have even attempted to relate blind-aided performance to the level of skill achieved by sighted people - even though the attainment of such a level is one professed aim of mobility-aid research.

2.4 DEDUCTIONS FROM PREVIOUS EVALUATION ATTEMPTS.

It is apparent that rigorous mobility evaluation would require an assessment of travel in different environments - city, suburban, rural, indoor, etc., and would necessitate the monitoring of many variables which are difficult enough even to decide upon and define, let alone actually measure.

Some of the evaluation methods already available give some useful, if mainly subjective, measures of "global" navigation skills in the larger environment. It would appear that a complementary approach using a controlled (indoor) environment and accurate instrumentation could lead to greater objectivity, provided realistic tasks were used. While attention would be restricted to a subset of overall mobility skills, since travel over long distances would not be possible, this limitation might be compensated for by the greater control over the

environment, and more accurate measurement, which ought to be possible. While indoor "obstacle courses" have been used before (18), the tasks chosen have been less than realistic, and instrumentation has not been available for accurate measurement of bodily motion. Solution of these two problems could offer some hope of improvement in mobility evaluation.

2.5 MOBILITY AS A CONTROL PROBLEM.

In adopting an objective approach towards mobility evaluation, it is helpful to use Kay's suggestion of regarding the mobile human as a complex control system, using the simplified model of Figure 2.1. In common with other control systems, there is a task, a "loop error controller" (the mental processor), a motor system, and a feedback network. Unlike other control systems is the fact that each of these elements is exceedingly ill-defined, and because of this Kay admits (1) that such a model is much too complex to analyse at present. However, this type of model is useful as long as some licence is allowed when discussing it.

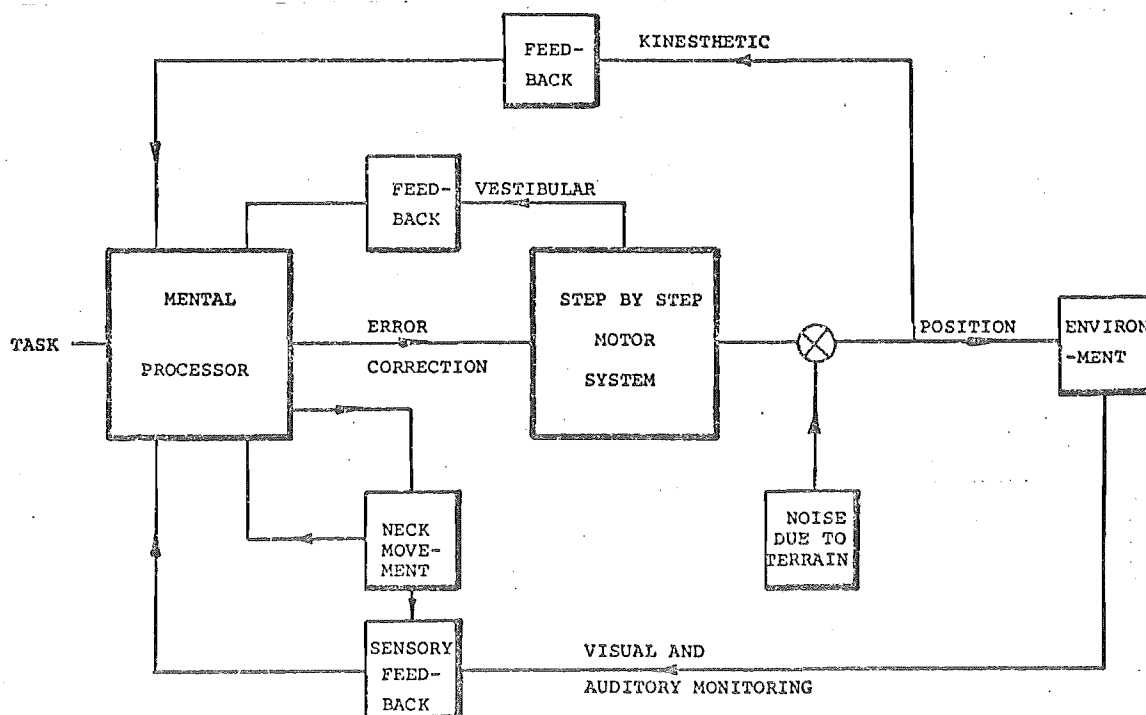


Fig. 2.1

Control System for Human Locomotion - Kay (1)

Normally, if a control system has unknown characteristics, it is possible to gain a better understanding of it by measuring its response to a simple input, and generalising to more complex inputs. In terms of the mobility situation, this means giving the subject an easily defined task, such as walking up to an object in a straight line, and measuring his error - in this case by how much he deviates from the straight line. Keeping the task simple, or at least easy to define, eases the task of measuring performance and estimating the quality of the overall control system.

An example of such a task was produced by Elliot et al (42) when he was devising training lessons for the Kay Sonic Torch. In this case, a row of bamboo canes was used for a number of exercises on walking parallel to a "shoreline". Subsequently, lessons designed to teach mobility skills using the Binaural Sensory Aid (24,25) used poles placed in various patterns for corresponding tasks involving body control. The tasks included:

- (i) Walking up to a pole from a distance of several feet;
- (ii) Walking around a square arrangement of poles, passing each at a distance of two feet;
- (iii) Walking along a row of poles spaced 6 feet apart;
- (iv) Walking between two straight rows of poles spaced 4 feet apart;
- (v) Walking in slalom fashion along a row of poles.

Of these tasks (i) - (iv) are well enough defined to show possibilities of measuring errors in the output of the control system if a suitable instrumentation system were available.

Is this type of task relevant to mobility? Let us investigate the original purposes of the tasks. The first task, for example, was designed to teach distance and direction cues while maintaining a

directed course. This task is an important one for pedestrians (aided or unaided) who need to approach specific places - pedestrian control positions, bus stops, letter boxes, parking meters, doors, etc. Task (ii) was designed to teach course construction through sensory aid input and proprioceptive feedback from the effect of locomotion over the ground. Task (iii) was to teach the maintenance of a course relative to a shoreline - probably the most common situation encountered in city or suburban travel. Task (iv) was designed to teach the control of body movement and the construction of a course in a cluttered environment. This again represents a very common situation - found in corridors, shopping malls, and environments crowded with pedestrians. The final task, slaloming, was intended to teach fine control of body movement and course planning.

Thus each task has its relevance to mobility, and this or a similar set of tasks may perhaps be chosen as a subset of mobility skills. Poles need not necessarily be used - these merely represent other objects found in the environment (walls, trees, etc.) which would serve equally well themselves with no added difficulty in measuring errors. In a laboratory situation, however, poles are very convenient.

Kay (1) considered these types of task so important in the overall mobility context that he devoted three of his "laws" to them, insisting that subjects must be able to execute specific control tasks before they can be considered mobile. Three such tasks which he considered basic to mobility are shorelining, walking perpendicular to an object (i.e. approaching an object), and walking past an object in the travel path. It was claimed (1) that these basic tasks and the others mentioned above helped the subjects to develop an awareness of spatial relationships, and that during early training 86 percent (later rising

to 97 percent) realized their relevance.

Even if these views are not accepted, it appears reasonable that in order to move gracefully through the environment, a pedestrian must have a high degree of control over his bodily movements relative to that environment. The types of task outlined above appear suitable for measuring the extent of this control, as they are well defined and possess at least some relevance to the complex overall mobility content.

Thus in the present thesis, measures of performance are developed which depend solely upon the subject's trajectory through the environment. These measures quantify the subject's skill in the control of his bodily path through the environment. This skill is termed "locomotor control", and is thought to be an extremely important subset of overall mobility skills.

It would be desirable to make simultaneous measurements of the subjective factors of performance such as the degree to which the subject feels strained or released, and the nature and quality of the perceptual map of "percept" he forms of his surroundings. Unfortunately the latter is almost impossible to measure or even describe during mobility, while most attempts to measure feelings of psychological tension of subjects performing mobility tasks have failed because the variables used for the purpose (e.g. heart rate, skin resistance, etc.) are found to be dependent on other attributes besides tension (34).

However, it is reasonable to argue that the mental processes of the individual will be manifested to some extent in the details of his body trajectory. For example, Armstrong (34) has suggested that step length is correlated with the subject's state of tension. Also, it is probable that a subject who (through deficiencies, in the sensory aid

under test or otherwise) has been unable to form an accurate cognitive image of his surroundings, will be unable to control his body accurately in its path through those surroundings.

It is not suggested that the approach taken in this thesis is all-encompassing. The techniques for performance evaluation based on the principles outlined above are put forward merely as a useful and objective addition to the methods used in the past.

REFERENCES

- (1) Kay, L.; "Towards Objective Mobility Evaluation: Some Thoughts on a Theory". AFB Monograph, N.Y., 1974.
- (2) Mann, R.W.; Mobility Workshop -- Appendix I. In R. Dufton (Ed.), Proc. Int. Conf. on Sensory Devices for the Blind, London : St Dunstan's, 1966.
- (3) Nye, P.W.; "Sensory Aids Evaluation : Procedures and Instrumentation". In R. Dufton (Ed.), Proc. Conf. on Sensory Devices for the Blind, London : St Dunstan's, 1966.
- (4) Benjamin, J.M.; "The Bionic Instruments C-4 Laser Cane". In P.W. Nye (Ed.), Evaluation of Mobility Aids for the Blind : Proceedings of a Conference. Washington, D.C.: National Academy of Engineering, 1970.
- (5) Leonard, J.A.; "Towards a Unified Approach to the Mobility of Blind People". AFB Research Bulletin, 1968, 18, 1-21.
- (6) Foulke, E.; "The Perceptual Basis for Mobility". AFB Research Bulletin, 1971, 23, 1-8.
- (7) Krigman, A.; "A Mathematical Model of Blind Mobility". AFB Research Bulletin, 1968, 17, 173-180.
- (8) Gibson, J.J.; "Visually Controlled Locomotion and Visual Orientation in Animals". Brit. J. Psychol., 1958, 49, 182-194.
- (9) Gibson, J.J.; "The Senses Considered as Perceptual Systems". London, George Allan and Unwin, 1966.
- (10) Lee, D.N.; "Visual Information During Locomotion". In R.B. Macleod and H.L. Pick, Jr. (Ed.), Perception : Essays in Honor of J.J. Gibson. Ithaca, N.Y. : Cornell University Press, 1974.
- (11) Johnson, I.R., White, G.R., Cumming, R.W.; "The Role of Optical Expansion Patterns in Locomotor Control". Am. J. Psychol. 1973, 86, 2, 311-324.
- (12) Collins, C.C., Scadden, L.A. and Alden, A.B.; "Mobility Studies with a Tactile Imaging Device". Conf. on Systems and Devices for the Disabled, Seattle, June 1-3, 1977.
- (13) Kay, L.; "An Ultrasonic Sensing Probe as a Mobility Aid for the Blind:." Ultrasonics, 1964, April-June.
- (14) Leonard, J.A., Carpenter, A.; "Trial of an Acoustic Blind Aid". AFB Research Bulletin, 1964, 4, 70-119.
- (15) Elliot, E.; "Evaluating a Sonic Aid for Blind Guidance : Part I. General Principles of Evaluation". In R. Dufton (Ed.), Proc. Int. Conf. on Sensory Devices for the Blind, London : St Dunstan's, 1967.

- (16) Elliot, E., Elliot, P.H., Roskilly, D.H.; "Evaluating a Sonic Aid for Blind Guidance : Part II. An Interim Report on the Aid". Ibid.
- (17) Cranmer, T.V.; "Evaluation of the Sonic Mobility Aid in Kentucky". Ibid.
- (18) Riley, L.H., Weil, G.M., Cohen, A.Y.; "Evaluation of the Sonic Mobility Aid". AFB Research Bulletin, 1968, 17, 181-120.
- (19) Sharpe, R.; "The Evaluation of the St Dunstan's Manual of Instruction for the Kay Sonic Aid". Report, University of Nottingham, Psychology Dept.
- (20) Elliot, E., Elliot, P.H., Roskilly, D.; "A Manual of Instruction for Use of the Kay Sonic Aid". London : St Dunstan's Evaluation Unit, 1967.
- (21) Russell, L.; "Pathsounder Travel Aid Evaluation : 1". In P.W. Nye (Ed.), Proc. Conf. on Evaluation of Mobility Aids for the Blind, Washington, D.C. : National Academy of Engineering, 1971.
- (22) Curtis, W.R.; "Pathsounder Travel Aid Evaluation : 2". Ibid.
- (23) Kay, L.; "Ultrasonic Spectacles for the Blind". In R. Dufton (Ed.), Sensory Devices For the Blind, London : St Dunstan's, 1966.
- (24) Kay, L.; "Sonic Glasses for the Blind : A Progress Report". AFB Research Bulletin, 1973, 25, 25-67.
- (25) Kay, L.; "The Design and Evaluation of a Sensory Aid to Enhance Spatial Perception of the Blind", Report No. 21, Dept. of Elec. Eng., University of Canterbury, 1973.
- (26) Airasian, P.W.; "Evaluation of the Binaural Sensory Aid". AFB Research Bulletin, 1973, 26, 51-71.
- (27) Ward, A.L.; "An Evaluation of the Ultrasonic Binaural Sensor in Rehabilitation of the Blind". Final Report, Arkansas Enterprises for the Blind, Little Rock, Arkansas, 1973.
- (28) Murphy, T.J., Johnson, N.C., Stealey, S.E., Kenji, I.; "Evaluation of the Binaural Sensor in the Rehabilitation of the Blind". Report from the Illinois Visually Handicapped Institute, 1973.
- (29) Thornton, W.; "Evaluation of the Binaural Sensor or Sonic Glasses". Research Report from St Dunstan's, 1973.
- (30) Armstrong, J.D.; "Monitoring Report of Blind Mobility Research Unit". Report, University of Nottingham, Dept. of Psychology.
- (31) Leonard, J.A., Wycherley, R.J.; "Towards the Measurement of Travel Skill". Proc. Conf. for Mobility Trainers and Technologists, M.I.T. Faculty Club, 1967.
- (32) Leonard, J.A.; "The Evaluation of Blind Mobility". AFB Research

Bulletin, 1973, 26, 73-76.

- (33) Armstrong, J.D.; "Evaluation of Mobility Aids". In N. Guttman (Ed.), Evaluation of Sensory Aids for the Blind, Washington, D.C. : National Academy of Sciences, 1972.
- (34) Armstrong, J.D.; "Evaluation of Man/Machine Systems in the Mobility of the Visually Handicapped". Report, Dept. of Psychology, University of Nottingham.
- (35) Armstrong, J.D., Worsey, R.C.; "The Adding of Visual Information to Previously Recorded Video-Tapes : A Functioning System". Quart. J. Exp. Psychol., 1972, 24, 351-353.
- (36) Armstrong, J.D.; "Summary Report of the Research Programme on Electronic Mobility Aids : 1967-1972". Report, Department of Psychology, University of Nottingham, 1973.
- (37) Nye, P.W. (Ed.); "A Preliminary Evaluation of the Bionic Instruments - Veteran's Administration C-4 Laser Cane". Final Report, Nat. Academy of Sciences, 1973.
- (38) Jansson, G.; "The Detection of Objects by the Blind with the Aid of a Laser Cane". Report No. 172, Dept. of Psychology, University of Uppsala, Sweden, 1975.
- (39) Jansson, G.; "The Effect of the Range of a Laser Cane on Detection of Objects by the Blind". Report No. 211, Dept. of Psychology, University of Uppsala, Sweden, 1977.
- (40) Collins, C.C., Scadden, L.A., Alden, A.B.; "Mobility Studies with a Tactile Imaging Device". Conf. on Systems and Devices for the Disabled, Seattle, June 1977.
- (41) Jansson, G.; "Human Locomotion Guided by a Matrix of Tactile Point Stimuli". Proc. Satellite Symposium on Active Touch, Pergamon Press, 1977.
- (42) Elliot, E.; et al.; "St. Dunstan's Manual of Instruction for the Kay Sonic Aid." London: St.Dunstan's, 1968.

CHAPTER 3

A FIRST STEP: COMPUTER SIMULATION OF ENVIRONMENT AND
DISPLAY.3.1 INTRODUCTION.

In urging a more objective approach to mobility aid evaluation, Mann (1,2) and others (3,4,5,6) have suggested using computers for simultaneously simulating and evaluating aids. Since computers deal only with numbers, data gathered from such a system must be quantitative at least to the extent of representation by a set of numbers.

Such an approach to aid development should have the advantage that a wide range of sensory aid display characteristics could be investigated by making relatively minor program changes, instead of long and costly hardware development processes. Mann (1) points out that simulator cost does not, like traditional research and development, escalate linearly with each different mobility device suggested and explored.

Also, the approach is consistent with the broad philosophy outlined in section 2.5, whereby attention is focussed on the subject's trajectory through a controlled environment.

In spite of these apparent attractions and several proposals for such studies, no project of this nature came to fruition until the present research commenced.

3.2 LIMITATIONS OF SIMULATION TECHNIQUES.

Authors proposing that computer simulation studies of blind

aids be performed have, naturally, tended to dwell mainly on the advantages (e.g. flexibility, objectivity, cost-effectiveness) to be gained. It is also necessary, however, to consider some of the limitations of such an approach, to avoid unrealistic expectations.

Firstly, it is possible to simulate abstract devices which may be unrealizable at reasonable cost. It can be argued that if a simulation suggests that optimum performance is obtainable from some display characteristic thought to be unrealizable, then at least an "ideal" has been defined, towards which to aim, even if the resulting real device matches only inexactly the simulated characteristics. However, limitations of cost and size dictate that some devices are more feasible to manufacture than others, and this problem of physical realization should not merely be ignored.

The opposite problem also arises - an exact simulation of any given existing device, especially one with a display rich in information, is likely to be virtually impossible to achieve. If such a device is simulated, care must be taken to reproduce at least its salient features, and to view any conclusions in the light of the differences between real and simulated systems.

3.3 A CONCRETE PROPOSAL.

It was thought at first that any attempt at monitoring the performance of a subject free to move in a large environment, while simultaneously presenting him with signals corresponding to a specified mobility aid would be too ambitious a project. It was therefore proposed instead to design a simulation system which used a hybrid computer to simulate both the environment and the mobility aid display, thus avoiding the telemetry problem involved in using a real

environment. Measures of performance could still be developed, which would be suitable for measuring the skills of a person moving in a real environment if it ever became feasible to build telemetry equipment of the required accuracy. If the latter did not prove possible, the simulation system with associated performance measurements could itself be used to investigate the effects of cue variations in improving or degrading performance.

In the event, more success than expected was achieved in developing a complete telemetry and simulation system, and it was not necessary to rely on the limited simulation described in this chapter for the above purpose. However, a description is included because this system not only prepared the way for more sophisticated techniques, but also represented in itself a unique contribution to objective mobility studies, and enables some insights to be gained into the mobility problem.

3.4 SYSTEM CONCEPT.

In terms of the simplified representation (Figure 3.1) of the mobile human executing a task using feedback from an artificial sensory aid, the interactive simulation described here replaces both the environment and the display by a computer. The blindfolded, stationary (seated) human subject delivers information to the computer - comprising head orientation, body orientation, and step commands. On the basis of this information, the computer calculates the position of the subject in some imaginary environment specified in the program, and generates appropriate headphone signals corresponding to the type of blind aid being simulated. The computer keeps a record of the subject's path, and at the end of a trial computes performance indices based on

his trajectory through the imaginary environment.

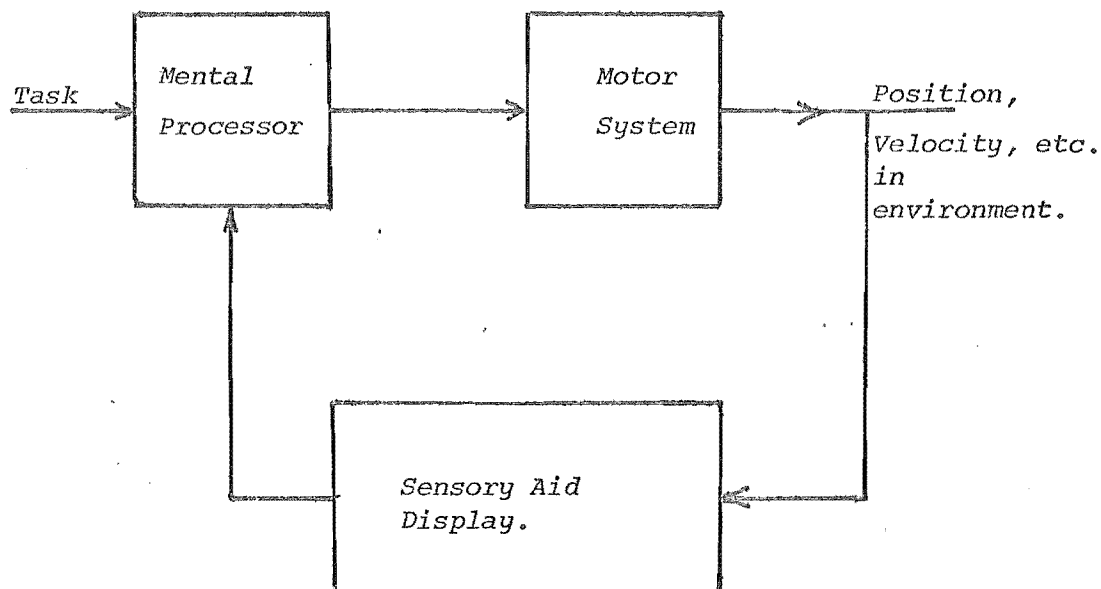
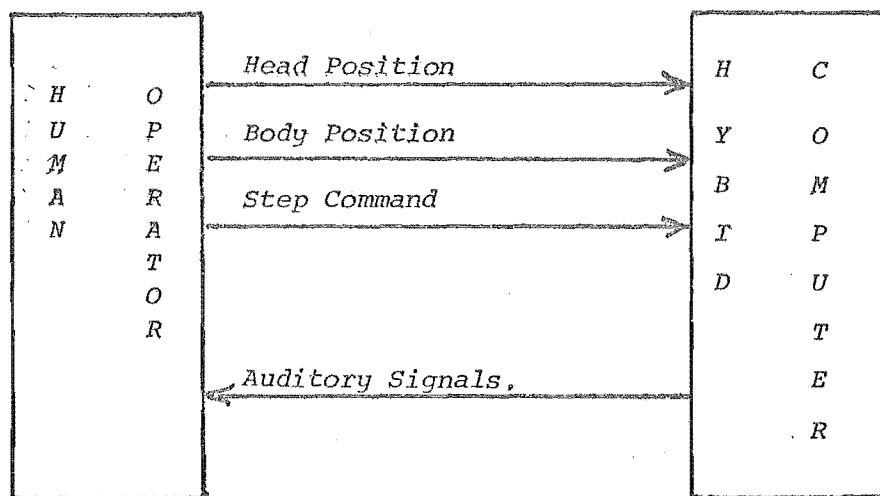


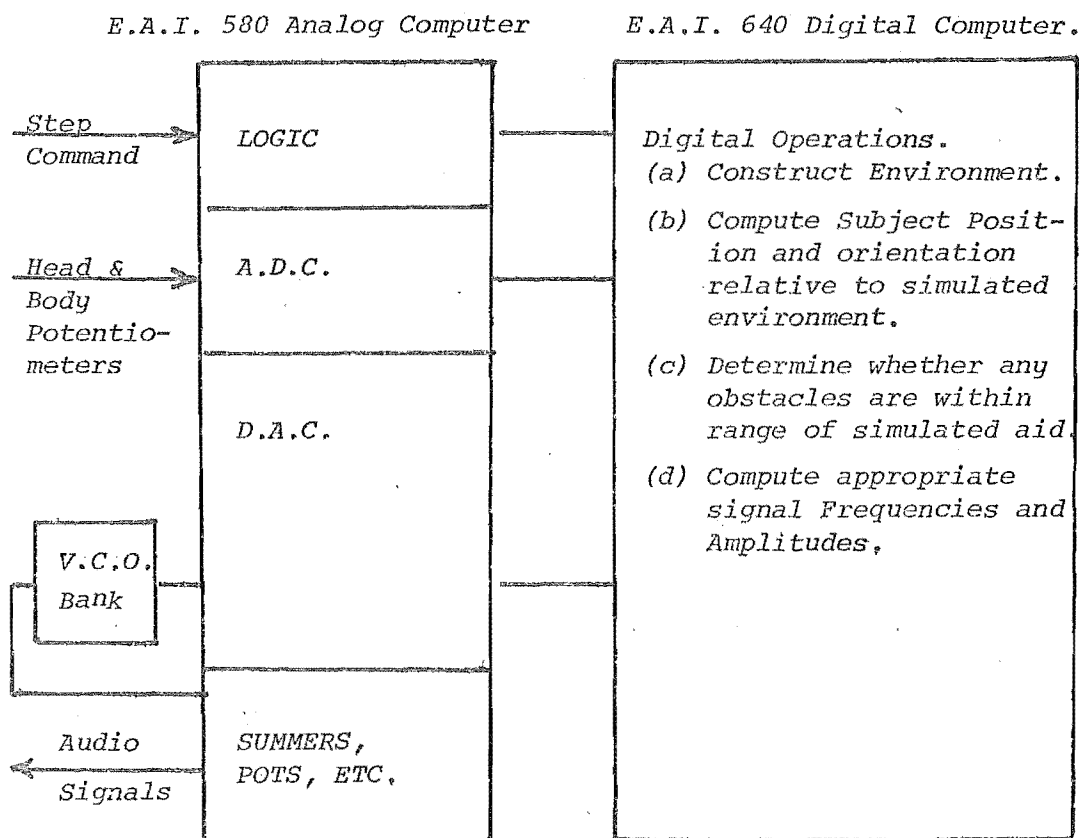
Fig. 3.1
Representation of Mobile Human.

3.5 DESCRIPTION.

The layout of the system is illustrated in the schematic of Figure 3.2, which includes a description of computer operations. Head and body orientation are fed into the analog computer, together with step commands, and these are sampled by the digital computer at a rate (approximately 20 Hz) determined by the amount of computation necessary between each sample. The subject is at liberty to take "steps" through the environment by depressing a switch. A "step" is defined with a constant length and possesses the direction indicated



(a) General Schematic.



(b) Detailed Schematic.

Fig. 3.2
Hybrid Simulation System

by the subject's body orientation. After each step, the computer calculates the subject's new position in the simulated environment.

The positions of obstacles in this environment are stored by the program. Using this information, together with the subject's calculated position, head and body orientation, and the characteristics of the auditory display it is desired to simulate, the digital computer decides which objects, if any, are within the "field of view" of the simulated device. The ranges and azimuths of these objects are calculated, and signals appropriate to the simulated aid characteristics are generated by the analog computer under digital control. An analog patching diagram appears in Figure 3.3, from which it can be seen that two independent signals (corresponding to two different targets), each with controllable frequency, amplitude and inter-aural amplitude difference can be presented to the subject. The waveforms of these signals are separately selectable, and can be sine waves, triangular, square, or variable mark-space ratio pulse trains.

Two sets of apparatus are available for monitoring the subject's motor responses - the "steering wheel" and the "electric chair". (Plate 1).

When using the "steering wheel", the subject takes "steps" by depressing a footswitch. His bodily orientation (and thus the direction in which a step is taken) is represented by the direction in which the steering wheel is pointed. Thus the wheel position represents absolute direction of motion rather than rate of change of direction as for a motor vehicle. In order that the subject may not receive any direction cue from the wheel (as he would, for example, if it were spoked), a smooth wooden disc is used.

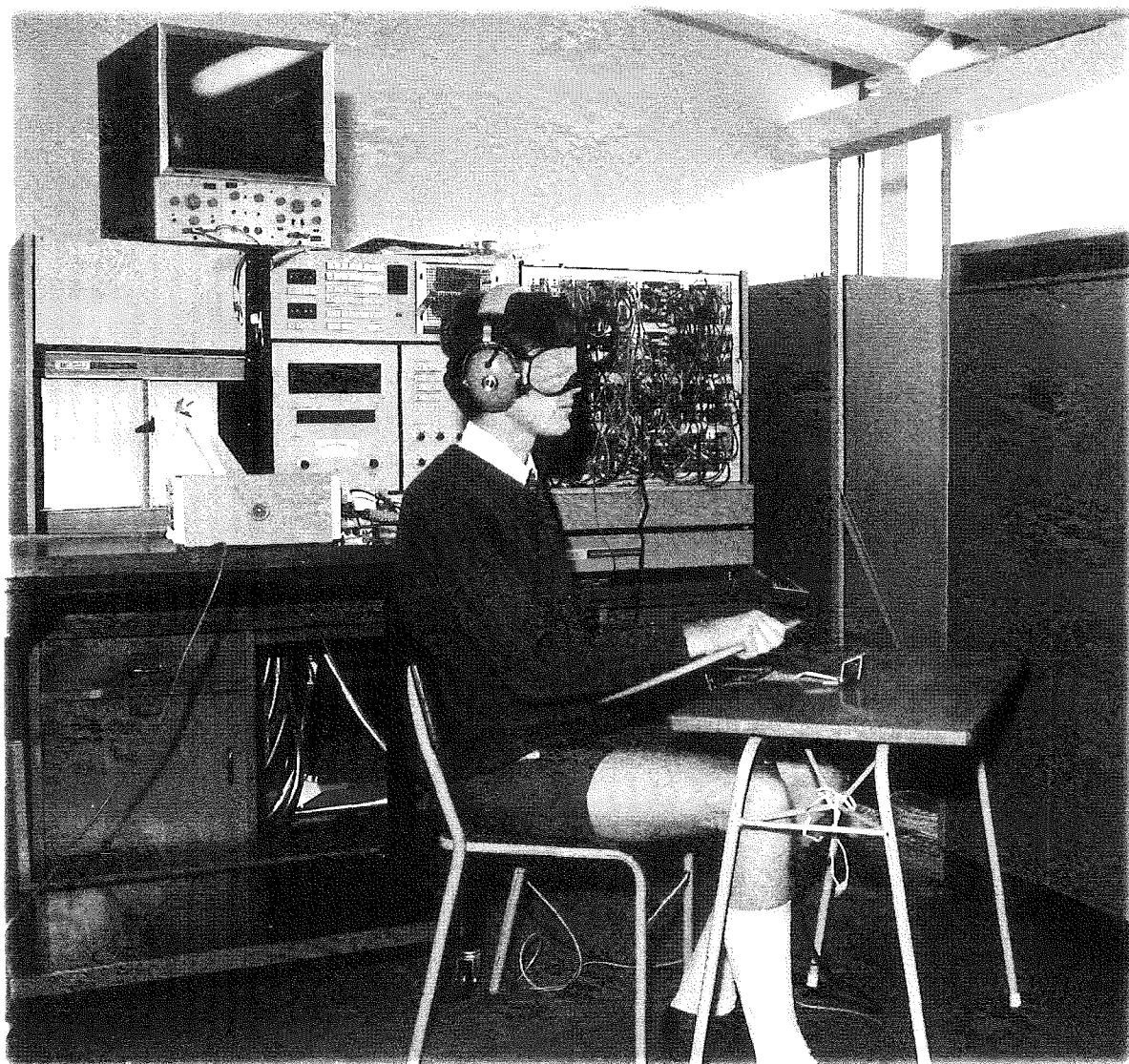


PLATE 1.

"Steering Wheel" Apparatus.

Between steps, the subject is free to "look" in any desired direction from his current position by merely rotating his "body" (the wheel). When using the "steering wheel" apparatus it must be assumed that the simulated sensory aid is body-mounted.

In order to simulate the effects of head movement, so that a subject could search the environment in directions other than that in which he is "walking", the "electric chair" apparatus (Plate 2) was constructed. This is a swivelling chair which incorporates a head harness connected to a potentiometer which monitors head movement relative to the body. Bodily orientation is represented by the angular position of the swivelling chair, whose bearings are sufficiently frictionless to allow free rotation under the action of light pressure exerted by the subject's feet on the floor. The "stepping" footswitch is replaced by a hand-held switch.

In all cases, a step length of 0.6 metres is used. The stepping procedure used in the system means that the subject "jumps" from one position to the next - i.e. steps are virtually instantaneous. Thus the display signals are also constrained to change discretely. In principle, this limitation could not be overcome if it was desired to retain the realism of the stepping switch - since a predictive system (unrealizable) would be required for speed estimation.

3.6 CHOICE OF DISPLAY.

It was decided to commence with a simplified form of the Binaural Sensor display for the purposes of initial investigation. Other displays were scheduled for study but the experimental program was overtaken and superseded by the development of the monitoring system described later.

The display of the Binaural Sensory Aid has been adequately described elsewhere (7) so a brief explanation only is offered here. Essentially, the display produces an auditory signal with a pitch proportional to the range of a target, and an Interaural Amplitude Difference (I.A.D.) proportional to its azimuth. Multiple targets can be simulataneously displayed, with the proviso that targets at different azimuths but similar ranges tend to merge into a phantom image somewhere between the real target positions (since two tones of the same frequency but different I.A.D.'s combine to form a single tone with one I.A.D.).

The complexity (in terms of spectral components) of the signal corresponding to a particular target depends upon the ultrasonic reflective properties of the target; but in general, targets such as poles, walls, windows, and inside corners result in close approximations to pure sinusoidal tones in the auditory display. A reflection from a bush, hedge, or other target with multiple reflecting surfaces which extend over many wavelengths in depth, results in a complex signal extending over a band of frequencies, centred upon the frequency corresponding to the mean range of the target. The blanking interval in the auditory display is approximately 10% of the 250 ms sweep time.

The salient features of this device (the range and direction codes) were relatively easy to simulate for one or two targets using the analog patching diagram of Figure 3.3. However, because the signal was constrained to change discretely rather than continuously, Doppler effects had to be omitted. Several other simplifications were made. The blanking intervals were ignored, as these contributed no information. All targets were assumed to be of the simple type, so that sinusoidal auditory signals could be used. Background noise due

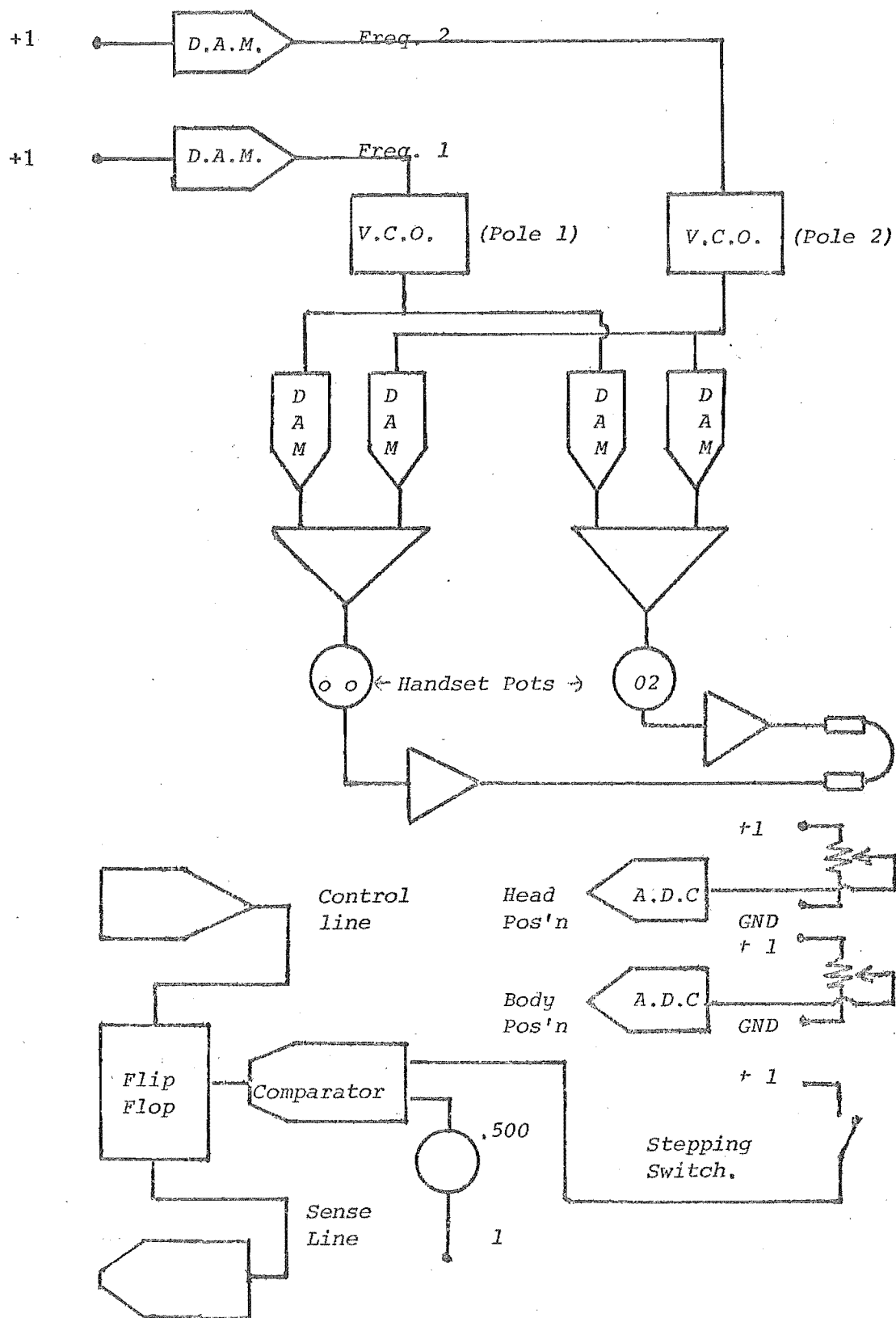


Fig. 3.3
Analog Computer Patching

to ground reverberation was omitted. The display was limited to a maximum of two targets at a time. This was necessary because only 6 Digital to Analog Multipliers were available on the analog computer. This, however, was not a severe limitation since the display of the Binaural Sensory Aid is usually very difficult to interpret with more than 2 targets present.

The beamwidth of the device was set at 60° , the range code used was 850 Hz/m, and the maximum range was 6.3 metres - all typical values for real devices. The I.A.D. characteristic was set to 0.5 dB/degree (at the upper limit of the commercial "Sonicguide" specifications), while the beamshape followed the idealized form (8) of the polar response of a flat transducer, i.e.

$$I = Ae^{-\frac{\theta^2}{K}}$$

Therefore, as in the real device, an additional cue to direction was provided by the falling off in overall volume towards each side of the beam.

In total, the display used for the purpose of the simulation was a somewhat abstract derivative of the Binaural Sensory Aid. Although the principal features of the aid concerned in locomotor control were simulated, the remaining differences were thought to be sufficient to urge caution in any generalizations made about the real device and absolute levels of locomotor performance. The latter consideration was also affected by the different human motor systems being used in the simulation (the wheel and the chair) and in a real environment (legs). However, it was thought that although absolute levels of performance were unlikely to be transferrable between real and simulated situations, relative levels of performance with different displays should provide valid comparisons. Here it should

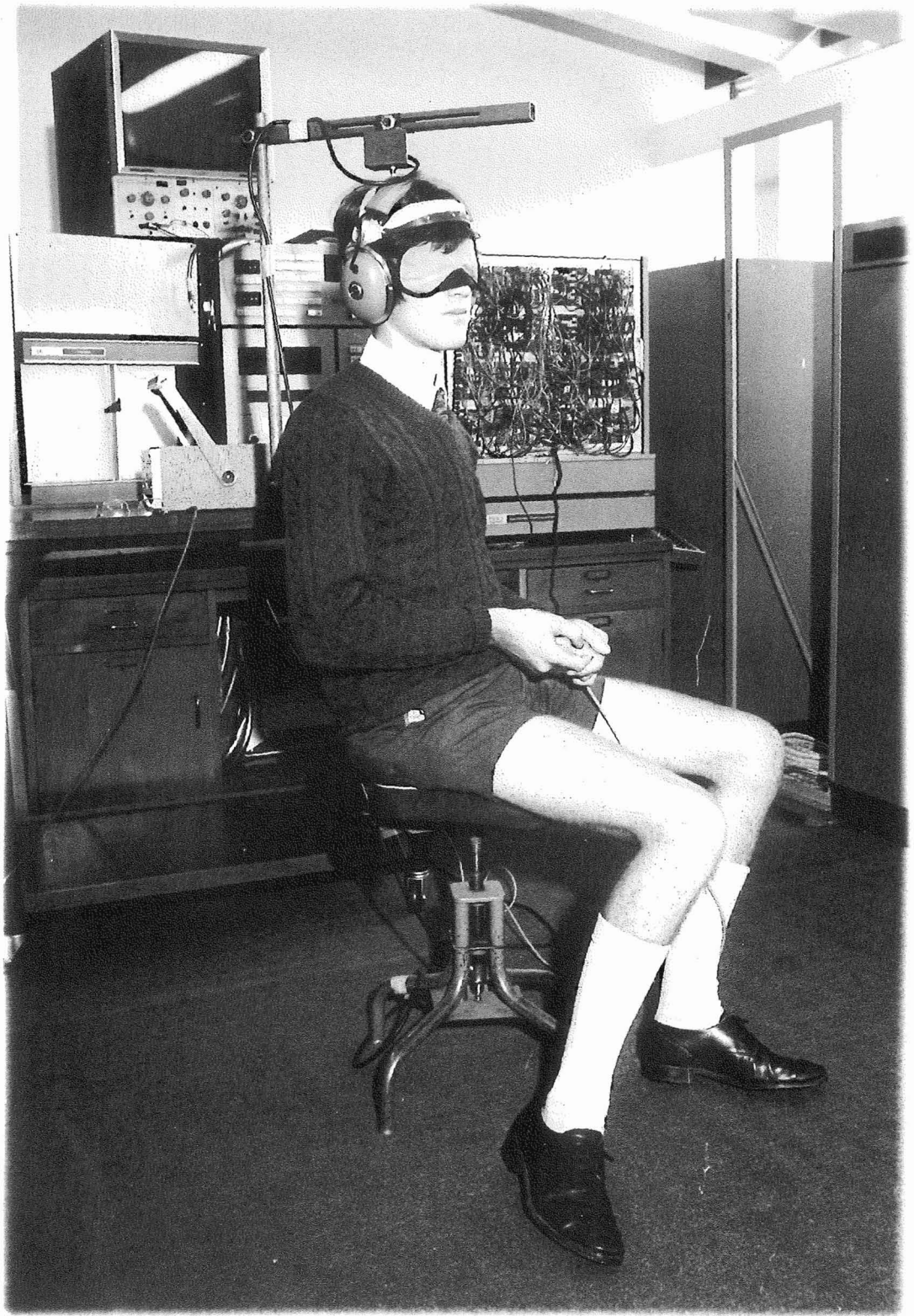


PLATE 2.
"Electric Chair" Apparatus.

be noted that despite the "discrete stepping" characteristic of the simulation system, many-obstacle-detector type devices could be simulated very realistically, since their outputs often (9,10) change only in discrete steps as range is varied.

3.7 CHOICE OF TASK AND EXPERIMENTAL PROCEDURE.

It was necessary to select a task which conformed to the broad philosophy of chapter 2 in that it had direct relevance to mobility and was amenable to relative ease of quantitative measurement. A "shorelining" task was therefore chosen, in which the subject was required to maintain a course 1 m distant from a long, straight row of poles spaced 4 m apart. In each experimental trial, the subject took 120 "steps" in the imaginary environment, and at the end of the trial various performance indices based on his trajectory were calculated.

The arrangement of the poles is illustrated in Figure 3.6. It can be seen that the first pole was placed 6 m away from the starting position. This was to enable the subject to become familiarized with the auditory display and to orient himself while only one pole was within range of the simulated aid.

Timing of each run was performed by the computer, and began as the subject took his first step. During the run, the subject's position was plotted at each step on a C.R.O. display (Figure 3.4) from which hard copies could be made. Thus the task could be performed under either visual or auditory control, and the path record was perhaps as useful as the numerical performance measures.

The instructions given to each subject are reproduced in Appendix I for the normal cue parameter combination outlined above. Separate sets of instructions were used for the wheel and chair systems.

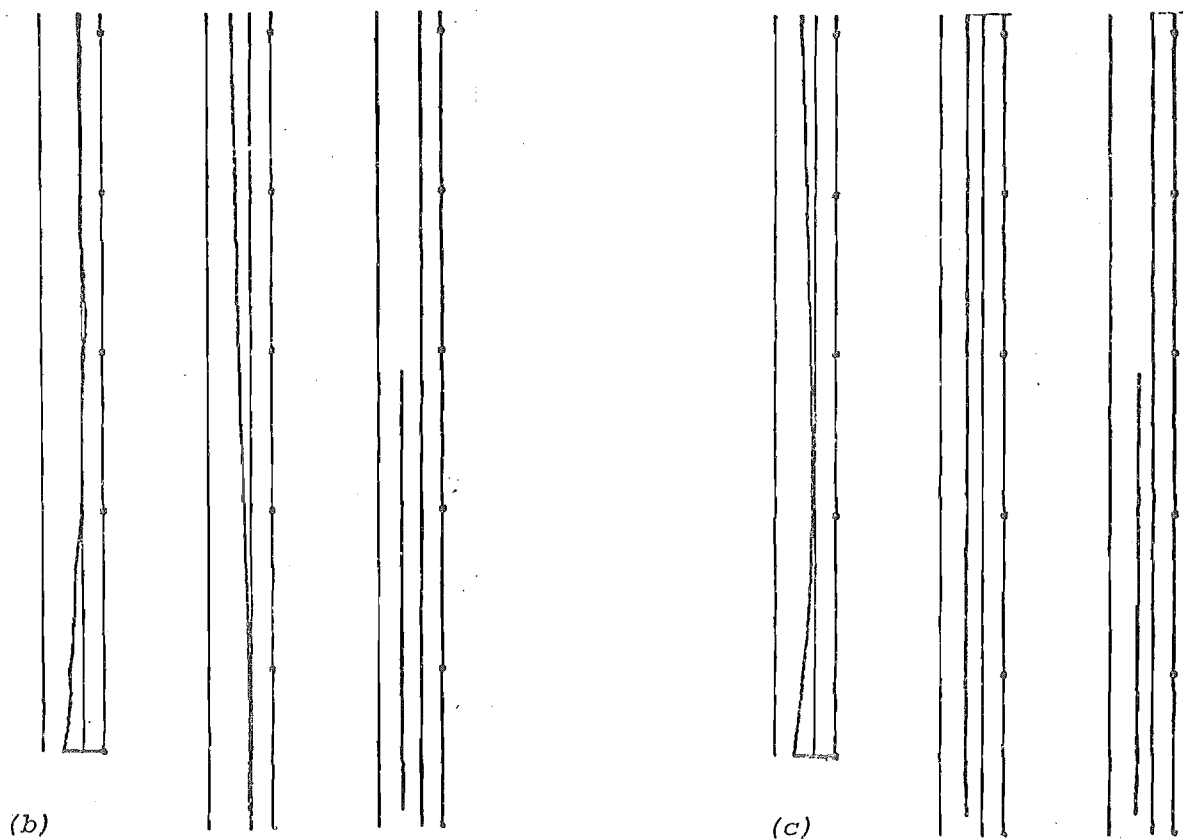
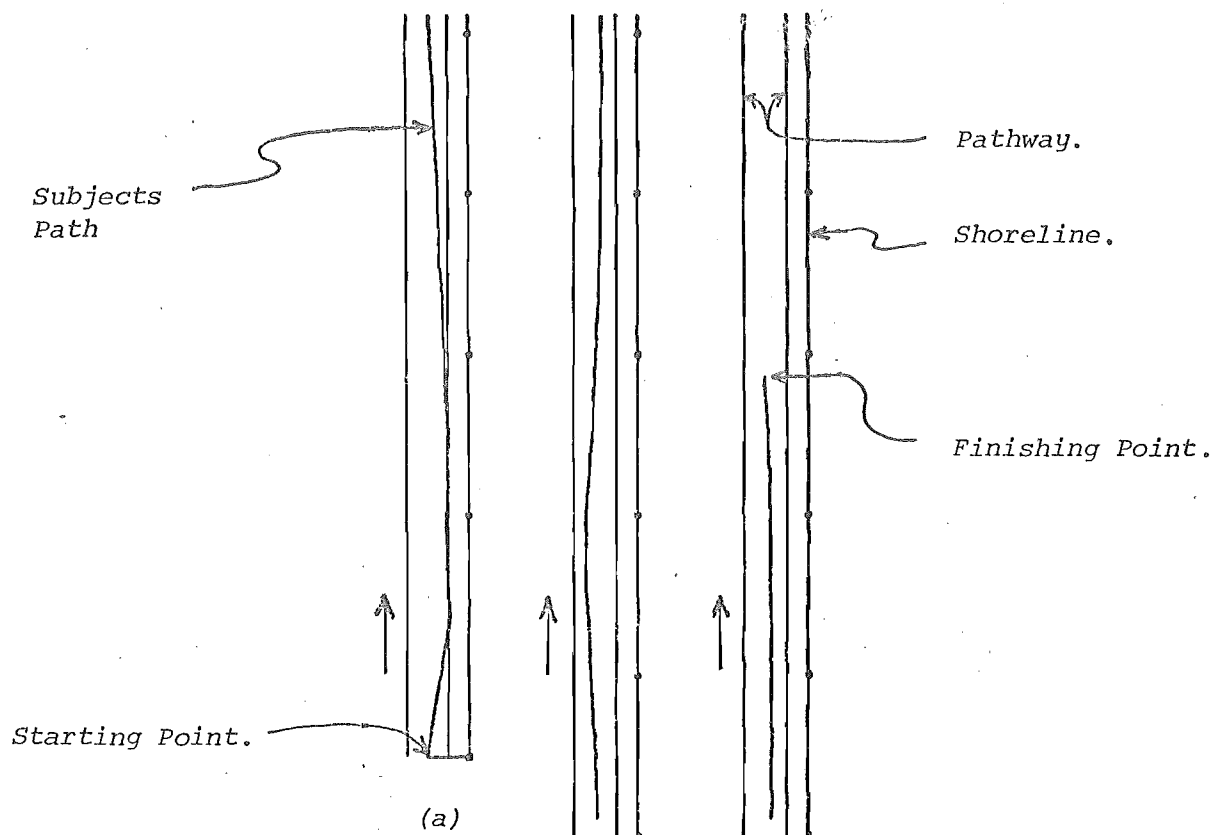


Fig. 3.4
Typical Path Plots.

3.8 PERFORMANCE MEASUREMENT.

During each experimental trial, the subject's trajectory was stored in three arrays which represented at each step the time taken and his x and y co-ordinates in the imaginary environment. These data were processed at the end of each trial to yield numerical indices of performance.

In developing these performance indices, it was decided to concentrate on mathematically simple quantities which could be easily understood in physical terms.

The starting point for the development of such measures was, however, not at all clear. Since the professed goal of mobility researchers is to raise performance to a level indistinguishable from sighted performance, it seemed logical to base any rating scale on sighted performance. It was not known, (nor could it be determined by the type of simulation described here) what sighted performance was. It was therefore decided that a geometrical ideal should be used, from which errors or deviations could be measured. For the shorelining task, this geometrical ideal was a straight line parallel to the shoreline and separated from it by 1 metre. Although "ideal" sighted performance might not correspond exactly to this straight line, it was hypothesized that both sighted and blind-aided performance could, in principle, be measured in terms of error from the line, and thence a direct comparison made between the two. The measurement of sighted performance would, of course, have to await the development of a suitable instrumentation system.

In summary, it was decided, in accordance with the hypothesis of chapter 2, to regard the mobile human as a control system with a

well-defined task (following a straight line) and measure the accuracy with which the task was performed. The RMSDIP measure (RMS Deviation from an Ideal Path) was defined on this principle, the r.m.s. process being directly applied to the subject's perpendicular distance from the "ideal path" at each step.

The subject's average speed (AVSP) was also measured, together with r.m.s. and mean deviations from average speed (RMSDSP and AVDSP respectively). These latter were intended to penalise subjects for excessive speed variations, it being hypothesised that a subject who stopped frequently or showed gross variations in speed was displaying poor and hesitant performance characteristics.

In an attempt to combine some of these performance indices, the following product was formed :

$$\text{"Goodness Factor" (G.F.)} = \frac{\text{AVSP}}{\text{RMSDIP}}$$

This was printed out together with the individual indices after each trial.

3.9 RESULTS.

3.9:1 System Trials and Validation

In the limited time during which research effort was concentrated on this apparatus, most of the experimentation performed was of an informal nature, calculated to obtain some idea of the value of the performance measurement and of the system as a whole. An initial step was to investigate the realism of the simulated display by testing a subject who had accumulated experience using the Binaural Sensory Aid. Such a subject was tested using the "steering wheel" apparatus with the cue parameters set to the nominal values detailed above. A

variation in the procedure for training subjects was made in that the first two experimental trials were performed under blindfold and recorded, without any practice trials under visual control. The paths for these two trials appear in Figure 3.4, and indicate that the subject was able to perform the task with some competence from a "cold" start. This suggests that little difficulty was experienced in transferring between real and simulated displays. Further improvement, however, occurred in a third run which was recorded after the subject was allowed one unblindfolded practice trial (Figure 3.4c).

The numerical performance measures obtained from these trials are listed in Table 3.1, and show a progressive improvement in speed (AVSP) over the three trials.

TABLE 3.1

*Experienced Sonicguide User : Initial Exposure
to Simulation System (Wheel Apparatus)*

<i>Trial No.</i> <i>Index</i>	1	2	3
<i>RMSDIP</i> <i>(cm)</i>	24.3	33.2	22.3
<i>AVSP</i> <i>(cm/sec)</i>	56.2	60.5	78.1
<i>AVDSP</i> <i>(cm/sec)</i>	4.3	3.8	5.8
<i>"GOODNESS"</i> <i>(sec⁻¹)</i>	2.31	1.82	3.50

The RMS Deviation from the Ideal Path (RMSDIP) varied between 22.3 and 33.2 cm (or approximately 9-13 inches) - a range of values which, although impossible to verify from real situations, appeared not

unreasonable from visual observation of subjects performing a real shoreline task using the Binaural Sensory Aid. A visual impression of the subject's ability to remain on the centre of the path can be gained from the plots of Figure 4. This impression supports the lower values of RMSDIP recorded for trials 1 and 3, compared with trial 2.

A second subject, who had had little exposure to real blind mobility aids, was able (after performing 8 shorelining trials in the usual manner) to slalom between the poles with little difficulty on the first attempt (Figure 3.5). The performance indices corresponding to this case appear in Table 3.2.

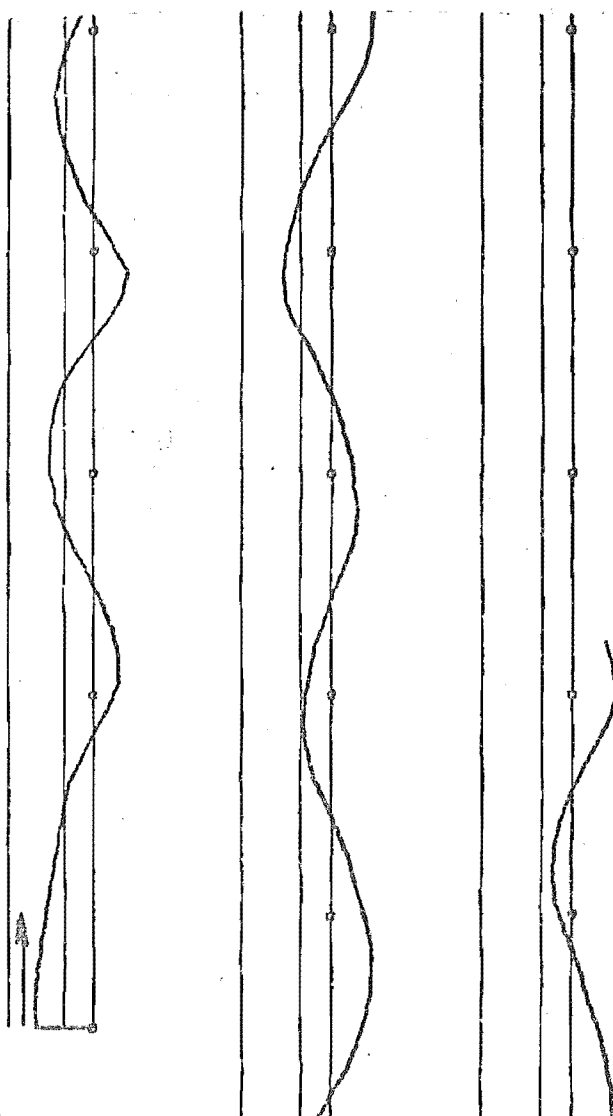


Fig. 3.5 : Slalom

As expected, the value of RMSDIP was very high, adding weight to the face validity of this measure in quantifying deviations from the centre of the "ideal" path.

TABLE 3.2

Experienced Subject : Slalom, Shoreline

Condition Index	Slalom	Shoreline (mean of 6 trials)	
		Normal Beam	Sharp Cut-off
RMSDIP (cm)	105.6	14.7	14.5
AVSP (cm/sec)	89.8	133.5	111.4
AVDSP (cm/sec)	7.0	9.5	7.7
"GOODNESS" (sec ⁻¹)	0.9	12.2	7.8

Average speed was comparatively high and no pole collisions occurred. This indicated that adequate information was available in the display to perform this reasonably difficult task.

In an attempt to investigate the ease with which parameters of the simulated device could be changed, several different direction cues were programmed. One variation tried was a sharp cut-off at the beam edge instead of the gradual fading produced by the above simulation. This modification was performed by specifying the intensities in the left and right channels as follows:-

$$I_R = K_1 e^{K_2 \theta}, \quad I_L = K_1 e^{-K_2 \theta}$$

where θ is the largest azimuth. Thus the inter-aural amplitude

difference of 0.5 dB/degree was retained.

This, and other modifications simulated, would be much more difficult to realize than the original cue; but it was of interest to explore whether such modifications were necessarily more satisfactory.

It was generally agreed amongst subjects who tried the sharp cut-off cue that it was more unpleasant and disconcerting than the normal condition. The actual level of performance attainable using the two cues, however, appeared to be similar, as shown in the results (Table 3.2) of 6 trials in each condition performed by a practised subject.

Although no statistical weight was attached to the results obtained, it was shown that changes in simulated device characteristics could be effected simply with minor program alterations.

3.9:2 Further Development of Performance Indices

From initial results it was noticed that subject trajectories were often obtained which, while not following the centre of the ideal path, were nevertheless parallel to the shoreline to a good approximation. This consideration led to the development of the RMSDSL measure (RMS Deviation from a Straight Line). More detailed discussion of this appears in Chapter 4. Briefly however, in calculating this measure the subject's actual average distance from the shoreline during the experimental trial was computed. A new straight line, parallel to the shoreline and separated from it by this average distance, was then used as the basis for measuring path deviations. Thus the subject was not penalized for choosing to follow the shoreline at a constant distance of other than one metre.

A further two performance indices were created by computing the Average Deviation from the Ideal Path (AVDIP) and the Average Deviation from a Straight Line (AVDSL). These new quantities were calculated on the same basis as RMSDIP and RMSDSL respectively, with the substitution of a modulus-averaging process for the root-mean-square process. It was thought that the ratio of RMS to Average could serve to give some numerical indication of the "peakiness" of the trajectory analogous to the "form factor" used to describe periodic waveforms.

Later developments were the introduction of a further measure of "Jerkiness" - namely the RMS Deviation from Average Speed (RMSDSP). This was designed to complement the AVDSP measure in the same way that the RMSDSL and AVDSL indices complement each other, since the RMS process weights large excursions from a mean more heavily than does the averaging process.

An attempt was later made to combine several aspects of performance in the shape of the "PERF" measure. This was defined in the following manner:-

$$\text{PERF} = \frac{\text{AVSP}}{\text{RMSDIP} \times \text{RMSDSP}} \quad \text{m}^{-1}$$

and was designed to penalize a subject for large deviations from a straight line and for high jerkiness, while rewarding him for high speed. However, it transpired that this combined measure showed very high variation from trial to trial (see Table 3.3) and the concept was not pursued further.

3.9:3 Comparison of Steering Wheel and Chair Apparatus

As mentioned above, most experimentation performed using the simulation system was of an informal nature. However, one subject was trained at length using the "steering wheel" apparatus and the normal display characteristics outlined above. His results over 54 trials in terms of RMSDIP, RMSDSL, and "Goodness Factor" are presented in Figure 3.6, in which it is shown that performance in terms of the first two indices settled to a stable range of values after approximately 20 trials. The means and standard deviations of the performance indices over the next 10 trials are listed in Table 3.3. Upon transferring to the "chair" apparatus, soon after this became operational, performance for the same subject had stabilized by the 9th trial (especially in terms of the RMSDSL measure), showing that no great difficulty was involved in adapting to the use of a new motor system. However, the new level of performance using the chair (summarized over the next 10 trials in Table 3.3) was poorer than that using the wheel system. The values of RMSDSL and RMSDIP were higher, indicating poorer path control.

TABLE 3.3.

*Wheel versus Chair
Mean of 10 Trials After Practice*

Condition Index	S#1		S#2
	Wheel	Chair	Chair
RMSDIP	14.5 (6.5)*	28.6 (14.5)	29.9 (12.7)
RMSDSL	7.9 (4.1)	13.9 (5.6)	18.5 (7.8)
AVSP	76.4 (16.1)	52.0 (9.9)	89.5 (3.7)
AVDSP	20.2 (16.7)	16.0 (18.5)	7.0 (2.3)
RMSDSP	-	21.4 (20.0)	12.9 (6.0)
"GOODNESS"	5.1 (2.2)	2.2 (1.0)	3.8 (2.5)
"PERF"	-	-	42.0 (43.6)

* Std. Deviation σ_{n-1}

This trend was tested by training a naive subject on the chair apparatus over some 37 trials. Again, performance had settled down after 20 trials, but as indicated in Table 3.1, in which the next 10 trials are summarized, was still poorer than that which the previous subject had obtained using the wheel.

These and other subjects tested informally on the chair apparatus all had some difficulty in co-ordinating head and body movements. A common tendency was for the subject to turn his head sideways to obtain correct-sounding signals while his trajectory diverged from the shoreline, without moving the body orientation to correct the error.

Average speeds were, on the whole, higher for the chair than for the wheel apparatus. This probably reflects the fact that it is easier to operate a handswitch than a footswitch at fast repetition rates. The ankle became noticeably fatigued in some cases when the wheel was used.

In summary, neither apparatus was completely satisfactory. The chair, while appearing to be more realistic, was more difficult to control and produced co-ordinating problems for the head and body. The steering wheel, while allowing more accurate performance, was less realistic and was tiring for the ankle.

Further improvements upon the basic apparatus were made. These included the raising, by the digital computer, of a control line on the analog computer during pole collisions - defined as occurring whenever the calculated position of the subject came within 0.3 metres of a pole. This signal could be used to activate a warning bell or light. In the absence of such a provision the subject had no real indication that a pole was being contacted, and indeed it was quite

possible for him to "walk" straight through a pole! However, in practice, collisions occurred so infrequently that this addition was not often used.

3.10 DISCUSSION.

The simulation system described above demonstrates that it is a viable proposition to use computer techniques to model mobility aid environment - display interfaces under dynamic conditions and to make quantitative measurements of the resulting man-machine performance. This represents a major advance on previous attempts to quantify display performance.

The flexibility of the technique is illustrated by the fact that changes in display parameters were easily made by minor computer program modifications, and it was similarly possible to change the environment. An example of the latter actually tried was to insert a "kink" in the shoreline at a position unknown to the subject, whose response was observed. A typical path plot (Figure 3.6) obtained under these conditions shows that the subject (at the first attempt) was able to identify the change in position of the shoreline and adapt his path accordingly.

The system proved valuable in deriving objective measures of locomotor control performance, and many of the indices so derived were to be used later on in the real environment, once suitable instrumentation had been developed.

However, the simulation system suffered from several limitations. The difficulty of interfacing to the human motor system in the most natural possible way was a major problem. The discrete stepping

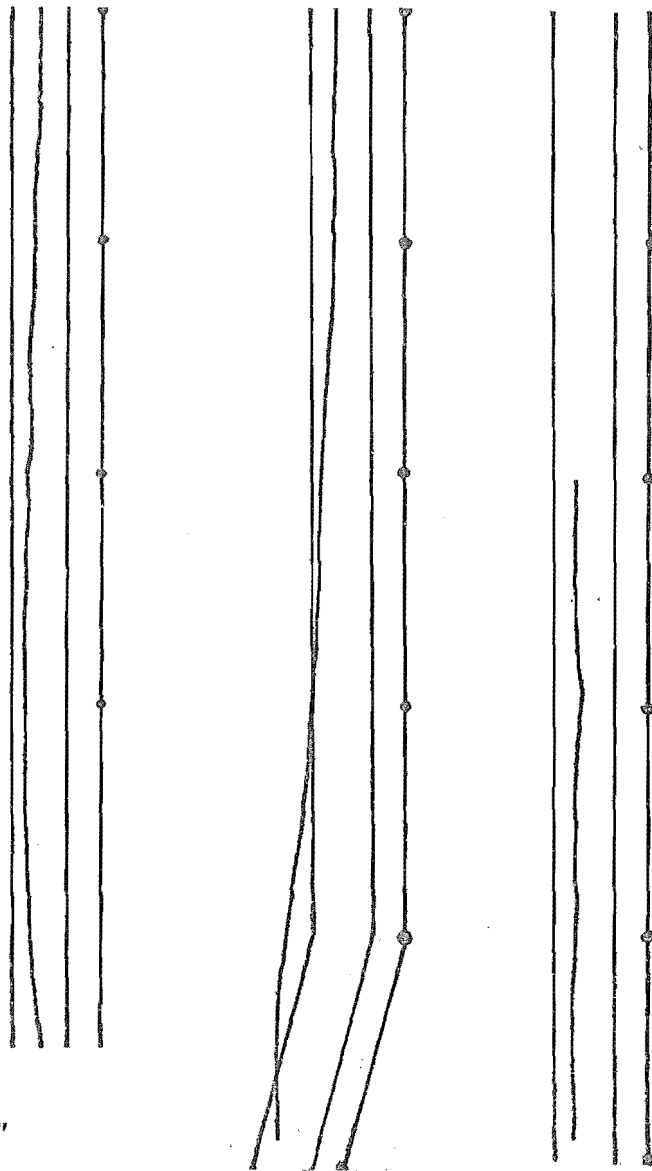


Fig. 3.6:
Path with "kink"

system used with both sets of interface apparatus described here prohibited smooth, continuous motion through the artificial environment, although it was felt that pressing a switch (especially with the foot) was a reasonable analog for real stepping. A continuous motion could be obtained using a foot pedal whose position represented velocity, or some type of bicycle-peddalling motion of the feet. The former was felt to be too far removed from walking, however, and even the latter would not be entirely natural.

Other problems encountered at the human motor interface included head and body co-ordination using the chair apparatus and the difficulty of deciding how best to monitor bodily orientation.

In summary, however, the system represents a significant contribution in the field of flexible mobility-aid display simulation, enabling a range of different display characteristics to be tested without the expense and time involved in building them. It also represents a major advance in the quantification of mobility performance in the type of locomotor control task described in Chapter 2. Finally, it provides a basis for further development, and much of the work described in succeeding chapters concerning display simulation and performance monitoring in a real environment derives directly from the experience gained from the simulation system described above.

REFERENCES

- (1) Mann, R.W.; "Mobility Aids for the Blind - An Agreement for a Computer-Based, Man-Device Environment, Interactive, Simulation System". Proc. Conf. on Evaluation of Mobility Aids for the Blind. Nat. Academy of Engineering, Washington D.C., 1971, pp 101-116.
- (2) Mann, R.W.; "Evaluation and Simulation of Mobility Aids for the Blind". AFB Research Bulletin, Oct. 1965, 1-62.
- (3) Mills, A.W.; "Toward an Empirical Theory of Mobility". Research Note, Dept. of Psychology, Tufts University, Medford, Mass., 1971.
- (4) Bliss, P.W., Nye, J.C.; "Sensory Aids for the Blind : A Challenging Problem with Lessons for the Future". Proc. IEEE, 1970, 58, 12, 1878-98.
- (5) Baecker, R.M.; "Computer Simulation of Mobility Aids : A Feasibility Study". AFB Research Bulletin, 1968, 16, 141-205.
- (6) Dupress, J.K.; "Sensory Aids Evaluation : Procedures and Instrumentation". Proc. Int. Conf. on Sensory Devices for the Blind, R. Dufton, Ed., London : St. Dunstan's, 1967, pp 293-7.
- (7) Kay, L.; "A Sonar Aid to Enhance Spatial Perception of the Blind : Engineering and Evaluation". The Radio and Electronic Engineer, 1974, 44, 11, 605-626.
- (8) Rowell, D.; "Auditory Display of Spatial Information". Ph.D. Thesis, University of Canterbury, 1970.

CHAPTER 4

A SECOND STEP :
MONITORING HUMAN LOCOMOTOR CONTROL PERFORMANCE

4.1 INTRODUCTION.

The desire for greater realism than was attainable by the simulation methods of Chapter 3 led to the design of an instrumentation system enabling continuous position monitoring of subjects who were free to move within a large laboratory area. Availability of such a facility would, it was hypothesized, remove the difficulties of interfacing human motor actions to the machine, while allowing greater diversity in environments than was achievable by the initial simulation. Both real and simulated mobility aids could be objectively examined in terms of the degree of control they gave the user over his bodily motions through the environment, and direct comparisons with sighted levels of performance should be possible.

Such a system would provide the first opportunity for a truly objective study of the sensory-locomotor control programs associated with blind mobility, using the philosophies discussed in Chapter 2.

The difficulties of implementation were, however, substantial, as evidenced by the fact that no practical instrumentation system of this nature had been built by other researchers, in spite of repeated proposals from several sources (1-6).

This chapter is divided into two main parts - sections 4.2 - 4.5 dealing with the design and analysis of the instrumentation system, and sections 4.6 - 4.8 treating the development and validation of computer-analyzed performance measurements based on the system.

4.2 INSTRUMENTATION SYSTEM DESIGN.

4.2:1 Specifications

The specification for the position monitoring system was that it should be capable of recording the position of a moving subject within a large, available laboratory (17m x 11m) with an error of not more than 2.5cm (1 inch). This tolerance was thought acceptable in view of the likely difficulties in defining the term "body position" precisely, and because minute displacements were thought unlikely to be important in the attempt to quantify performance.

4.2:2 Possible Configurations

It was not immediately obvious what form the proposed monitoring apparatus should take. The relatively short distances involved virtually ruled out convenient use of radar or any form of radio wave. Limitations on accuracy together with considerations of cost and complexity militated against a possible television and computer picture processing system (7). Air sonar systems have been proposed by other authors, and at least two (1,2) claim to have reached an experimental stage of operation, although one operated over a distance of only 2 metres, while the other gave measurements only at one-second intervals. These systems appear to have been discontinued.

Several possible ultrasonic ranging systems were considered for the present work, but an ultrasonic solution was basically undesirable because of interference problems arising from the probable need to operate the monitoring system in conjunction with ultrasonic mobility aids. Some of these, such as the Sonic Glasses, operate over a very wide band of frequencies, extending from 40 - 80 kHz for the normal adult version ("Sonicguide") to 80 - 160 kHz or higher for experimental children's versions.

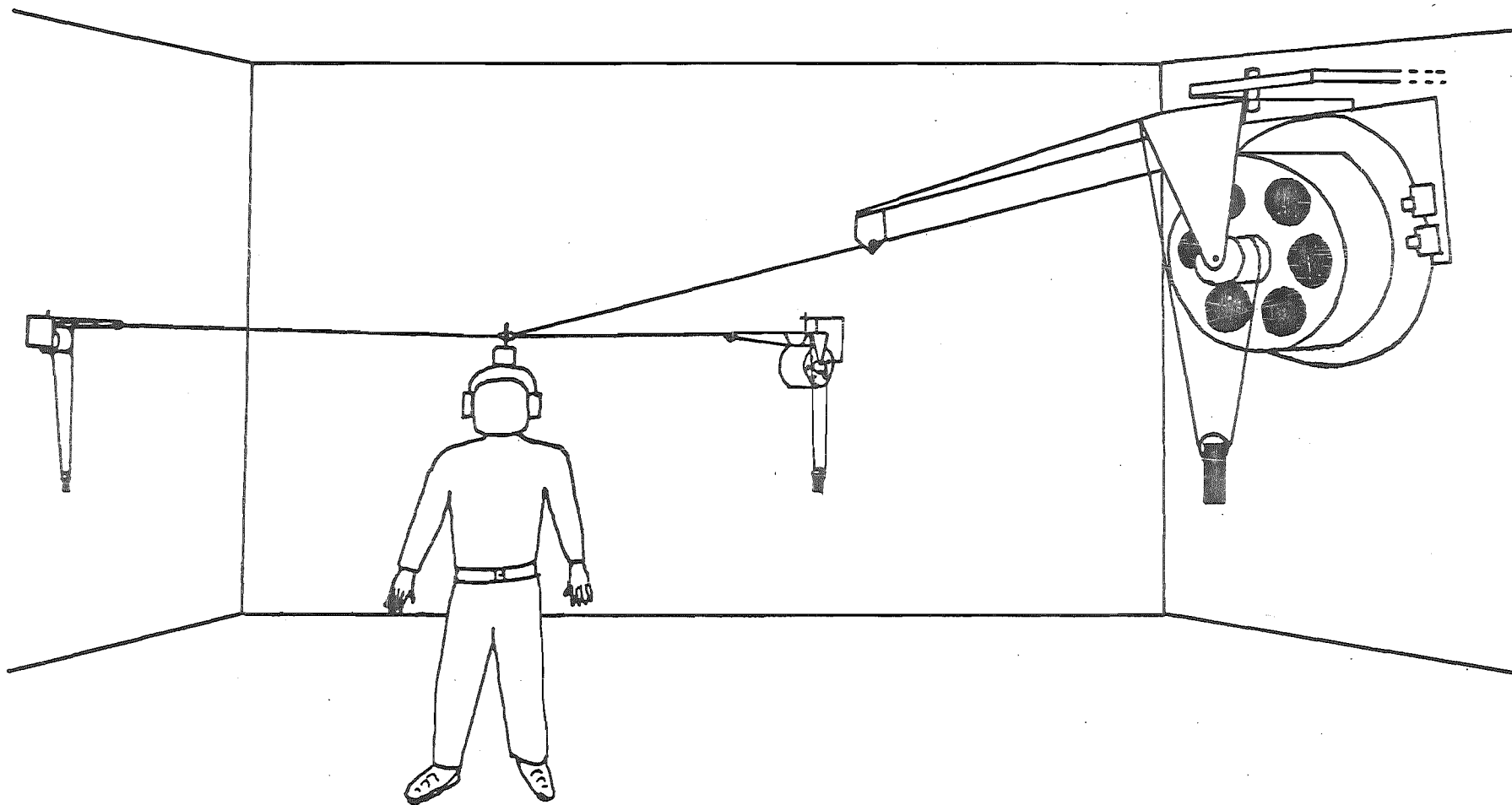


Fig. 4.1
Physical Arrangement

Any system using analysis of films or videotapes would clearly be inaccurate and not adaptable to fast, on-line computer processing. An apparatus using collimated light beams along the walls was suggested, but would have required an excessive number of elements (1200) for the required accuracy.

The technique eventually adopted uses mechanical position sensing by means of very light dacron lines attached to the subject (Figure 4.1). This has proven considerably more effective than originally expected, and combines high accuracy with relative simplicity and low cost. (11,12,13).

4.3 SYSTEM DESCRIPTION

4.3:1 Mechanical Sensors

The general physical arrangement of the system is illustrated in Figure 4.1, and a system block diagram appears in Figure 4.2. Three light lines are attached to the subject, either via a short pole strapped to his back or via a light-weight linkage surmounting his head. These lines are led to three fixed points arranged in an approximately equilateral triangle around the periphery of the room. At these points the lines are wound on to take-up drums of 10 cm diameter. The functions of these drums are to keep the lines tensioned and to facilitate measurement of the changes in string lengths by the monitoring of drum rotation.

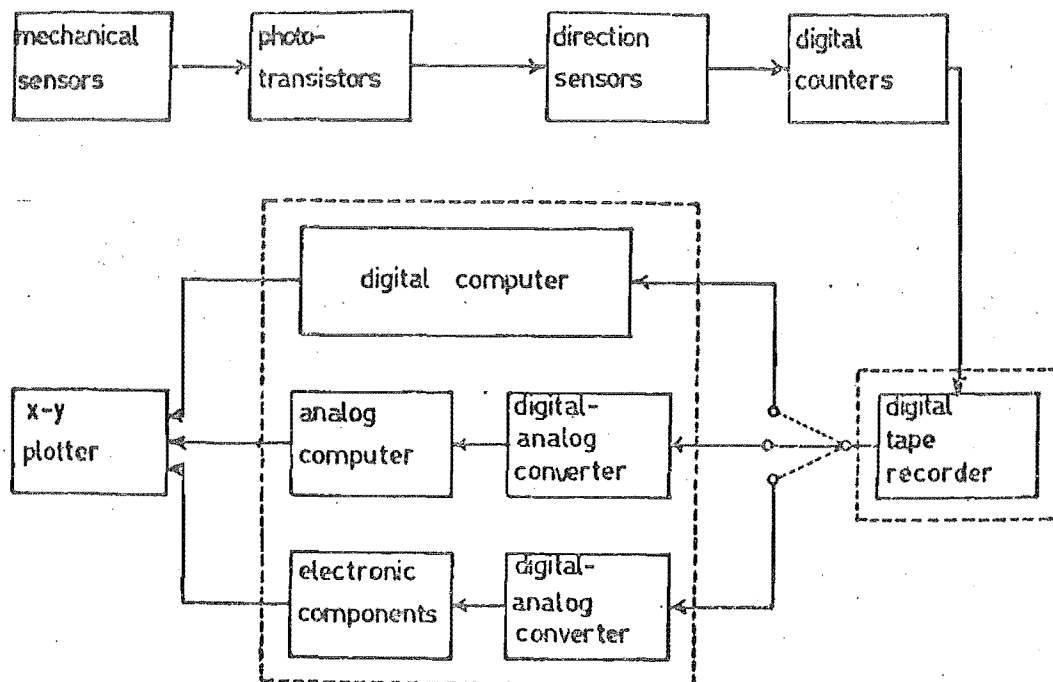


Fig. 4.2

System Block Diagram

4.3:2 Tensioning Method

One of the drums is detailed in Figure 4.3. Coaxial with each drum, and on the same shaft, is a smaller drum or pulley of 1.9 cm diameter, around which is wound a separate length of line. A weight of 360 gm wt is suspended from this tensioning line via a block rove to advantage, giving a downward-acting force of 180 gm wt under static conditions. This results in a nominal tensioning torque of 342 gm cm which varies by only 5% for subject accelerations of up to 0.5 g.

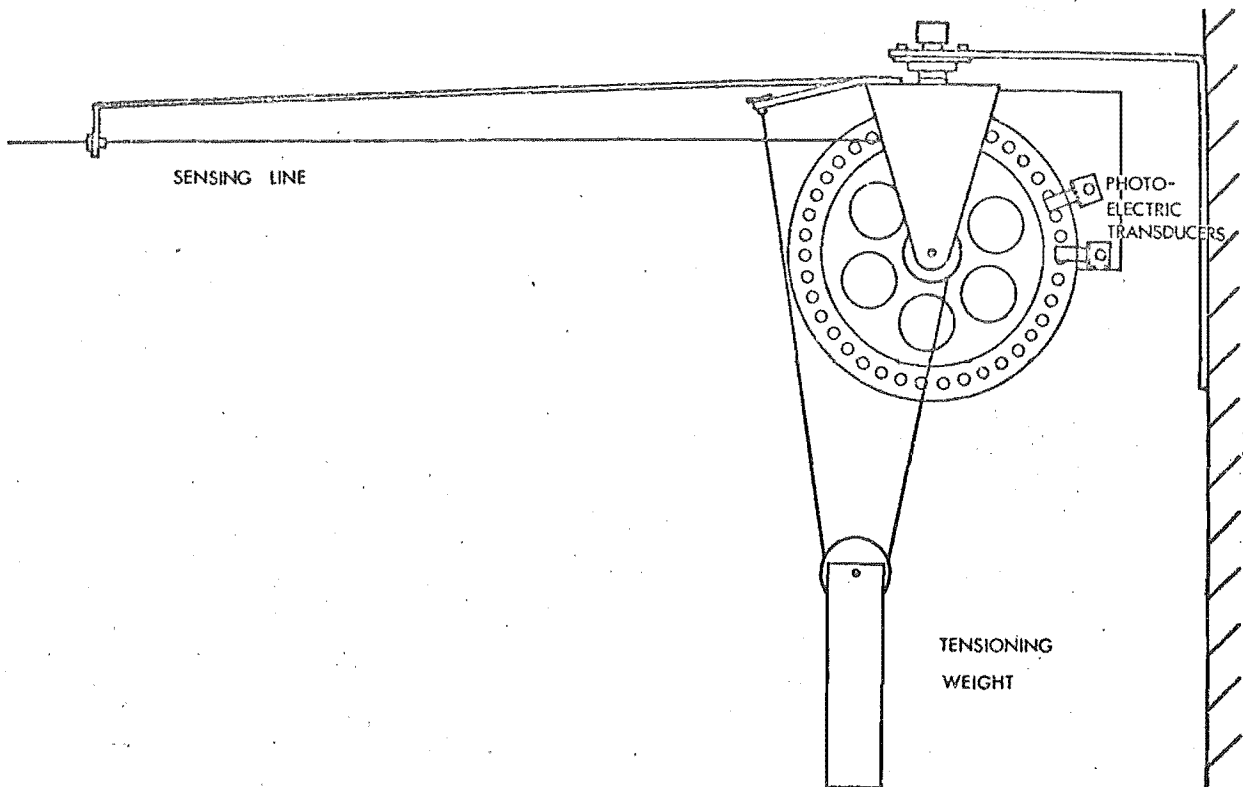


Fig. 4.3.

Tensioning Drum Detail

The effect of this torque is to give a tension in each measuring line of 33 gm wt under conditions of zero acceleration. For non-zero acceleration the inertia of the drums (500 g.cm^2) results in variations from this nominal value.

Published data (9,10) on human locomotion characteristics include tachistograph results (yielding graphs of the velocity of the lower trunk for subjects constrained to walk in a straight line) and "stick diagrams" constructed using interrupted light photography. These indicate that the maximum magnitude of acceleration achieved during normal walking is in the region of 0.25 g. An acceleration

of 0.3 g towards or away from a drum is calculated to result in variations of $\pm 20\%$ from nominal tension. An analysis of the ensuing errors is given in Section 4.4 below. While these errors would be reduced by using higher line tensions, it was thought desirable to keep the forces acting upon the subject to such a low value that he would not normally be conscious of them. A psychophysical experiment (11) performed using various values of tension showed (with a confidence level of 0.9) that nett forces of less than 50 gm wt are undetectable when acting through the harness worn for pole mounting of the sensing lines. The experiment was performed under controlled conditions in which the subject was asked to concentrate exclusively on estimating the direction of an applied force. A similar experiment for head-mounting revealed a lower threshold of 10 gm wt. However, under normal experimental conditions subjects coupled to the apparatus with head-mounting report no consciousness of any outside forces when performing normal mobility tasks.

4.3:3 Line Length Monitoring

The operation of the monitoring system as a whole depends upon measuring the lengths of two of the lines attached to the subject. The two take-up drums used for this purpose are located at opposite ends of the laboratory's longest wall, while the third drum and associated line merely assist in balancing the forces acting upon the subject.

The rotation of each of the two measuring drums is monitored digitally by a light-chopping system. The circumferential flanges of these drums are perforated with regularly spaced holes, each of which corresponds to a 0.8 cm change in line length (see Figure 4.3). The widths of the holes and the spaces between them are equal. On

each drum, straddling the perforated flange, two L.E.D. - photo-transistor pairs are located $2n+1$ hole radii apart (where n is any integer). When a drum rotates, its two phototransistors produce square waves (labelled A and B in Figure 4.4) displaced in phase by one hole radius. The number of hole spacings traversed is recorded on a 12-bit digital counter. The counter is incremented when a positive going transition of waveform A (Figure 4.4) occurs while B is low, and decremented when a negative going transition of A occurs with B low.

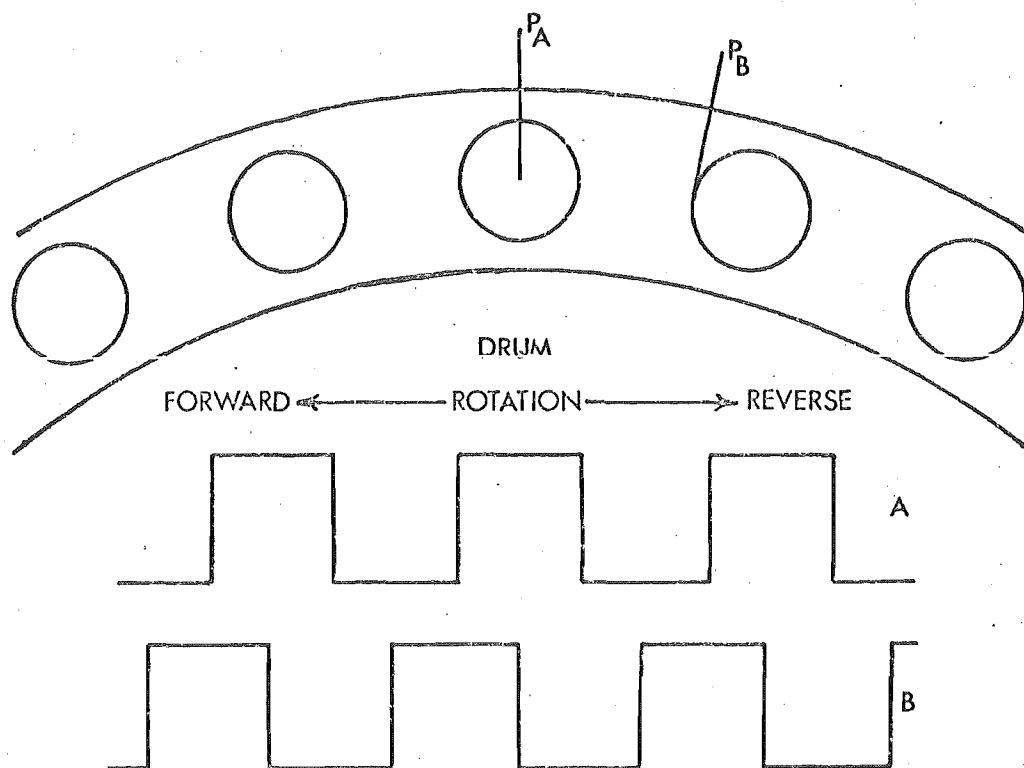


Fig. 4.4

Drum Rotation Direction Sensing. The two Photo-electric Transducers, located at P_A and P_B , give rise to the voltage waveforms A and B respectively.

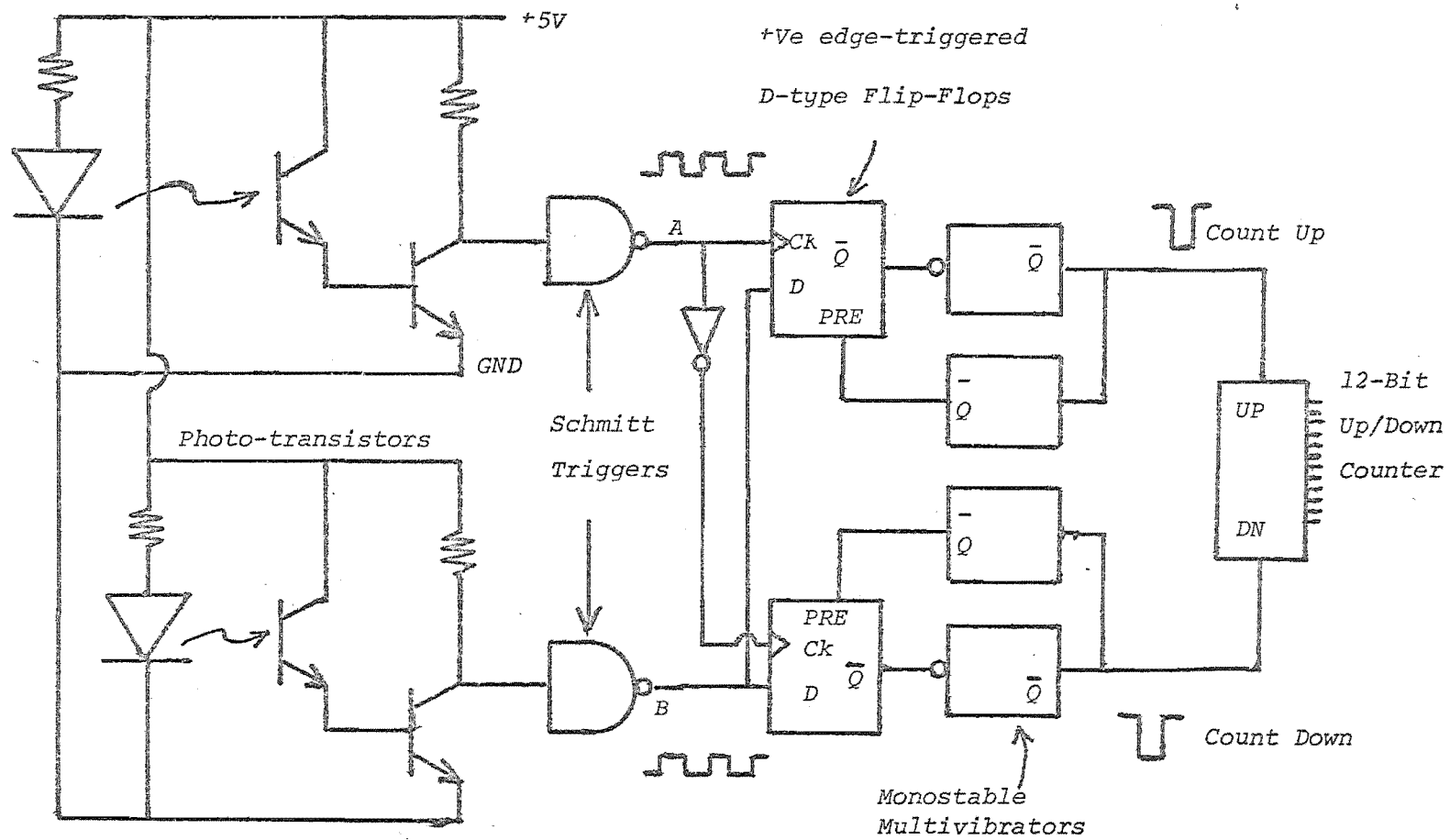


Fig. 4.5
Direction Sensing and Counting Circuitry.

Circuiting to perform the waveform generation, direction sensing, and counting functions appears in Figure 4.5, and is duplicated for each drum.

When the two counters (one for each measuring drum) are initialised correctly, their binary outputs directly represent the lengths of the corresponding lines in multiples of 0.8 cm. The counting and direction sensing circuiting for both drums is contained in a single control unit, and counter initialization can be performed by depressing a switch on the unit. Counter contents at initialization time are determined by 24 toggle switches, the settings of which can be varied according to the position in the room it is desired to use for calibration. Visual checking of counter contents is provided for by an L.E.D. display.

4.3:4 Solving for Position

The two 12-bit counter outputs, representing the distances (d_1 and d_2 in Figure 4.6) of the subject from the two measuring drums, are sampled periodically by a digital computer (EAI 640). The computer solves the relevant geometrical equations to obtain x and y co-ordinates.

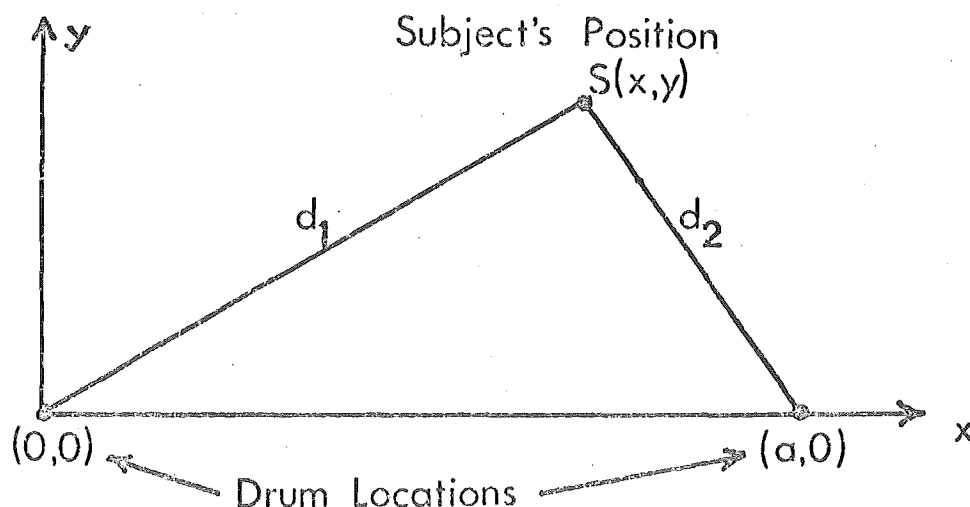


Fig. 4.6

Geometrical Arrangement

With reference to Figure 4.6, it is readily shown that

$$x = \frac{a^2 + d_1^2 - d_2^2}{2a} \quad \dots\dots\dots (4.1)$$

$$\text{and } y = \pm\sqrt{d_1^2 - x^2} \quad \dots\dots\dots (4.2)$$

where a is the constant separation of the two measuring drums.

Because these two drums are at opposite ends of a wall, the subject cannot cross the x -axis. Thus the possible ambiguity in the y -coordinate is removed, and the positive sign is used in 4.2.

A sampling rate of 5 Hz is normally used, but this is variable from zero to 60 Hz.

In order to expedite the completion of the system to a stage where its feasibility could be tested, an analog computer (EAI 580) was initially used in place of the digital machine. The two 12-bit counter outputs were routed for this purpose into 12-bit D-A convertors. The analog patching network of Figure 4.7 was used to solve equations 4.1 and 4.2 to produce x and y co-ordinates, which were displayed directly upon a precision $x - y$ plotter. This system had the advantage that user time was more readily available on the analog than on the digital computer.

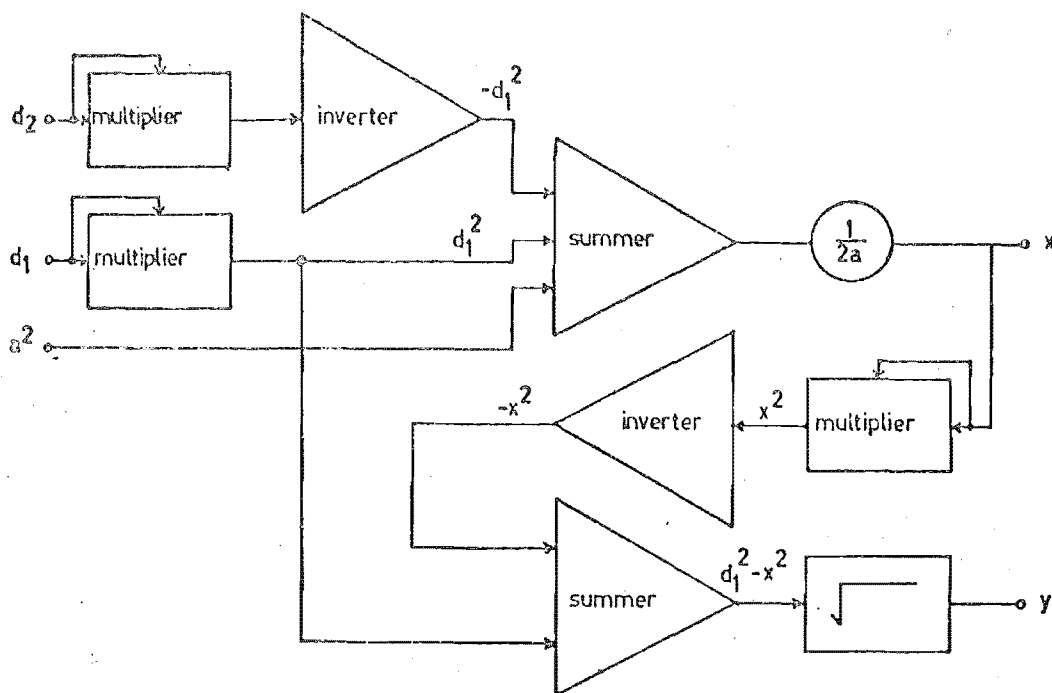


Fig. 4.7
Analog Patching Diagram

4.4 SYSTEM ACCURACY.

Errors in position measurement arise from the following factors:

- (i) Fluctuations in line stretch;
- (ii) Line sag;
- (iii) Hole spacing in drums;
- (iv) Computation errors in the solution of the equations.

Since a 32-bit word length is used for the computations, errors of type (iv) should be negligible in comparison with the other three types when the digital computer is used. Factors (i), (ii), and (iii) result in errors in the measurement of the line lengths d_1 and d_2 , and in order to estimate their effects upon the co-ordinates x and y , it is necessary to differentiate equations 4.1 and 4.2 above with respect

to d_1 and d_2 , yielding:

$$\frac{\partial x}{\partial d_1} = \frac{d_1}{a} \dots\dots\dots(4.3)$$

$$\frac{\partial x}{\partial d_2} = \frac{-d_2}{a} \dots\dots\dots(4.4)$$

$$\frac{\partial y}{\partial d_1} = \frac{d_1(1 - \frac{x}{a})}{y} \dots\dots\dots(4.5)$$

$$\frac{\partial y}{\partial d_2} = \frac{xd_2}{ya} \dots\dots\dots(4.6)$$

For known errors in d_1 and d_2 , constant error contours may be found by setting the moduli of these partial derivatives to constant values. Setting them all to unity will produce the contour along which a given error in d_1 or d_2 will give rise to an equal error in w or in y . This contour is represented by :

$$d_1 = a \dots\dots\dots(4.7)$$

$$d_2 = a \dots\dots\dots(4.8)$$

$$y = (a - x) \sqrt{\frac{x}{2a - x}} \dots\dots\dots(4.9)$$

$$y = x \sqrt{\frac{a - x}{a + x}} \dots\dots\dots(4.10)$$

and is plotted in Figure 4.8.

Within the unshaded region of Figure 4.8, the error in either co-ordinate will be less than the sum of all the errors in the measured lengths of both sensing lines. These errors may now be analysed.

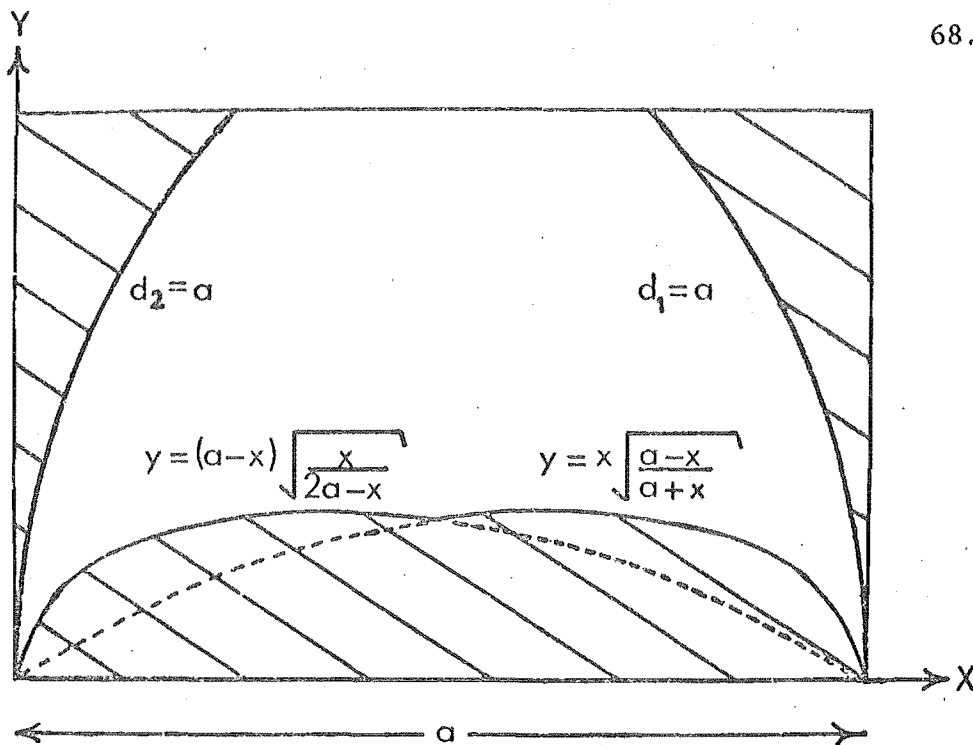


Fig. 4.8

Laboratory Floor Plan Showing Error Contours.

Within the unshaded region, the error in either co-ordinate is less than the sum of the errors in the lengths of the two sensing lines.

The stretch in the line used is 0.028 cm/m at the nominal tension of 33 gm wt. A little thought shows that this fact in itself produces no error, as the entire line is merely lengthened by about 0.5 cm, and remains in that state unless acceleration of the subject occurs. Accelerations of 0.3g towards or away from a drum will vary the line tension by 20% (due to the inertia of the drum and tensioning weight), producing a maximum error (when the line is fully extended to 17.4 m length) of 0.11 cm due to line stretch variation. The increment, δs , in line length, L , due to sagging can be approximated by

$$\delta s = \frac{w^2 L^3}{24 T_0^2} \dots\dots\dots (4.11)$$

where w is the weight of the line per unit length and T_0 is the tension at the lowest point in the line. The practice has been adopted of initialising the counters when each line is well extended

(to a length of, say d_c metres). In this case the error in measurement due to sagging of a line extended to d metres is given by:

$$\delta s = \frac{w^2}{24T_0^2} (d^3 - d_c^3) \dots\dots\dots(4.12)$$

If d_c is chosen so that the junction of the two lines lies near to the centre of the laboratory, the errors due to sag will be small around this most-used region. In this case the largest error which can result in the operating region of Figure 4.8 will occur when one line is fully extended (to 17.4m) and the other is at zero extension. If the value of d_c is chosen to be 8.7m, the sag error at this position will be 0.55 cm in one line and 0.1 cm in the other. Errors due to quantization of measurement (type (iii)) have a maximum possible value of 0.8 cm for each line. Thus the maximum possible error in either co-ordinate is 2.25 cm under static conditions. With a 30% variation in line tension, the sag error will be 0.9 cm in one line and 0.1 cm in the other. An error due to stretch variation of 0.11 cm is also introduced, raising the maximum possible error in either co-ordinate to 2.71 cm. This is slightly outside the original specification (which was arbitrary) but could easily be improved upon by reducing the quantization errors (type (iii)).

An analysis of the effects of the above errors on the derived indices of performance appears in section 4.6:7 below.

4.5 SOFTWARE.

A flow chart (Figure 4.9) illustrates the arrangement of system software. The two counters which monitor line length are sampled at a rate determined by typed commands. At each sampling

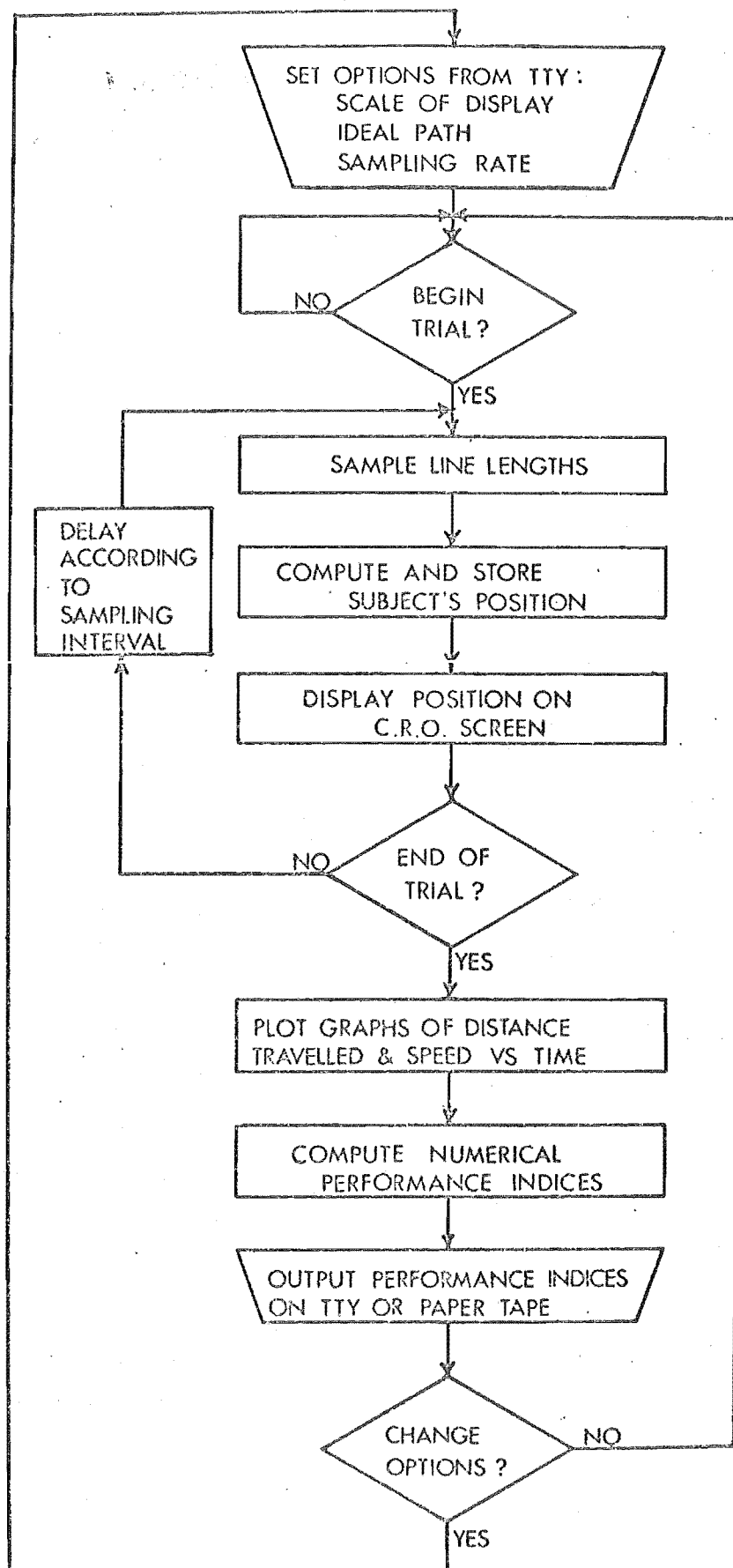


Fig. 4.9

Monitoring System Flow Chart

interval, position is computed, stored, and plotted on a C.R.O. storage display. The scale of the display and the portion of the room displayed can be varied on-line by typed commands, and if desired the subject's path can be replotted to a different scale after the trial is over. The positions of obstacles can be specified and displayed on the screen.

Programming is mainly in Fortran, but Assembly language is used where it is necessary to interface with the computer's interval timer and with the Binary Data Interface (B.D.I.) through which the incoming data from the line length counters is sampled.

Timing of each experimental trial, which is performed by the interval timer mentioned above, is started and terminated by push-buttons (sense-switches). Communication between the computer operator and the subject in the laboratory is maintained by an intercom and a small closed circuit T.V. monitor with recording facilities.

An effort has been made to simplify the system's operation as far as the user is concerned, and several people unfamiliar with computer systems have been able to operate it.

4.6 DEVELOPMENT OF PERFORMANCE INDICES.

4.6:1 Path Plots

As originally constructed (using analog computation), the apparatus provided a record of performance in the form of a plot of the subject's travel path; obstacle positions could also be marked on the plot. Errors in the performance of certain tasks, such as passing too close to obstacles, could be measured directly from the plot.

At this stage of development a back harness and pole arrangement was used for attachment of the sensing lines, and it soon became evident that body sway was amplified by this arrangement so that variations in gait were noticeable on the path plots. Figure 4.10 shows two plots obtained from a subject walking (a) quickly and (b) slowly.

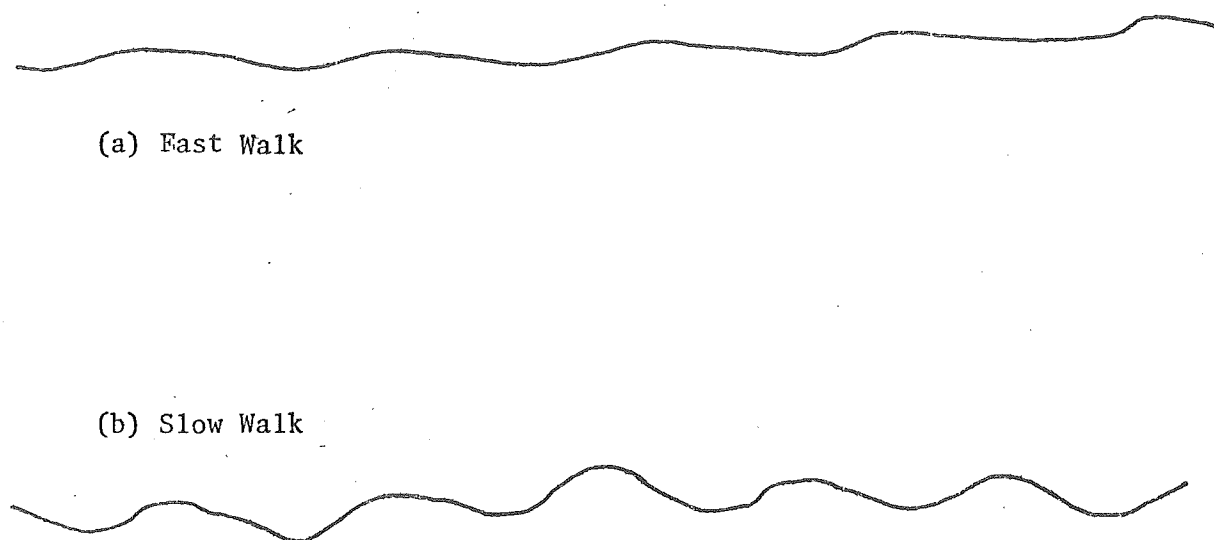


Fig. 4.10
Effect of Speed on Gait

The periodic swaying of the subject's body was more noticeable for the slow walk than for the fast one.

Apart from this effect, there was no direct indication on the path plots of the subject's speed. An illustration of the confusion this could cause was given by an experiment using two subjects. Figure 4.11 shows an arrangement of poles which was initially unknown to the subjects. The task was to circulate around the poles, keeping

them always at a constant distance to one side.

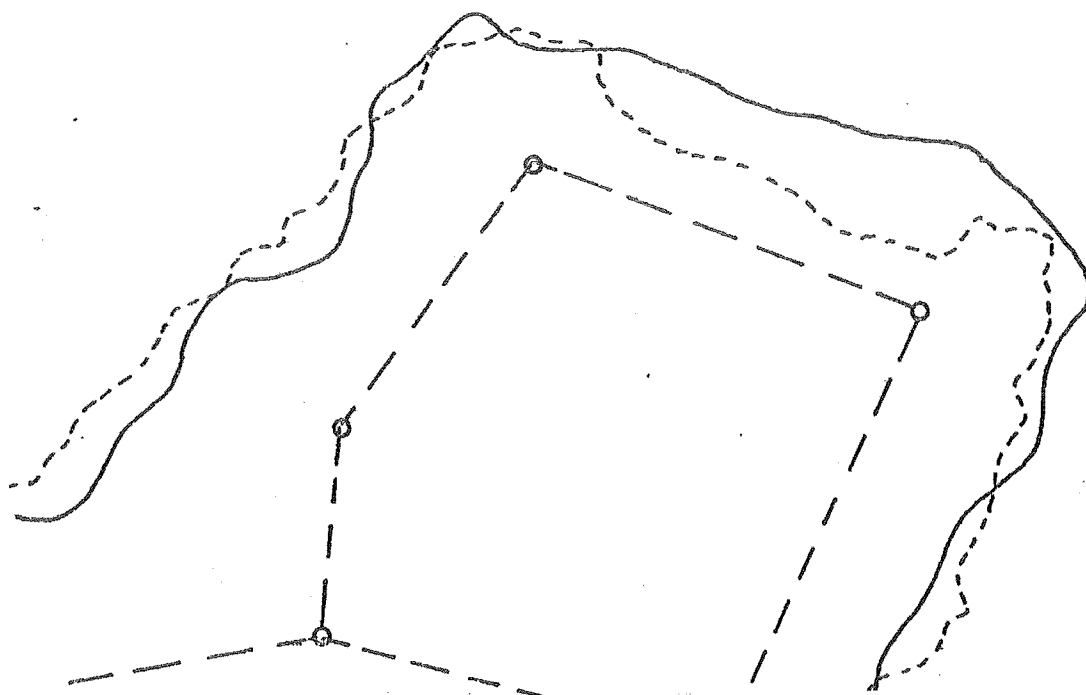


Fig. 4.11

Path Plots Illustrating Need for Speed Indication

The two paths shown were produced, respectively, by an experienced Sonicguide user and a subject using the Single Object Sensor recently developed at Canterbury (14). While both path plots appear to reflect equal competence, one subject (the Sonicguide user) executed the task much more quickly and smoothly than the other. Whether this variation reflected differences in the properties of the two devices or in the experience of the respective subjects, it was clear that some method of explicit speed indication on the plots would make them more valuable. Thus when the system was converted to digital computation, the program was modified to insert crosses on the

position plot at intervals selectable on-line by a typed command but normally set at one second.

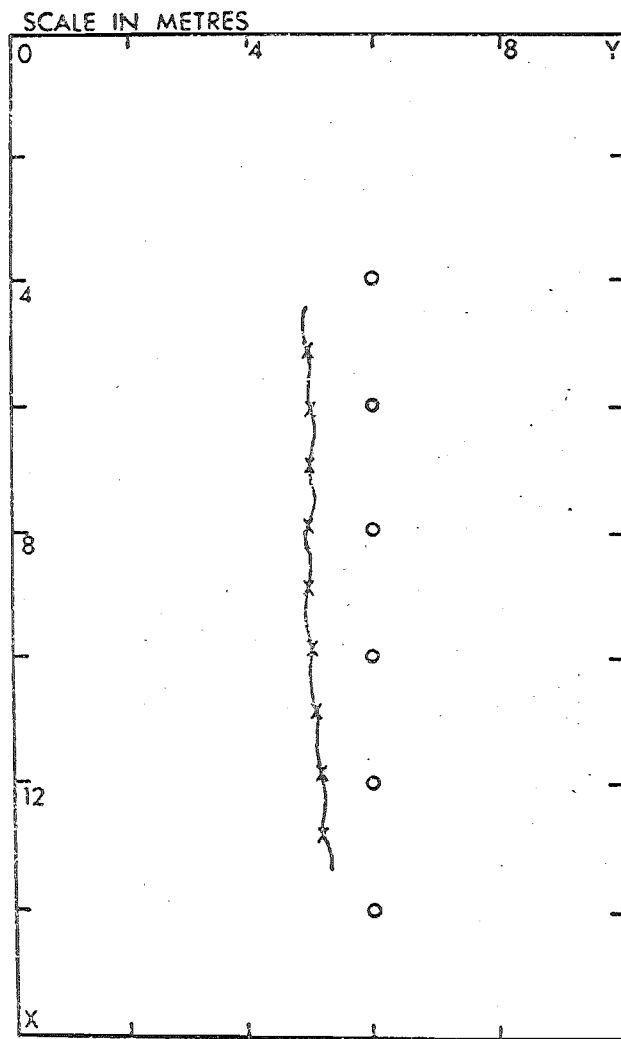
Using this technique, gross variations in speed are apparent from a perusal of the path plot (Figure 4.12), the subject's speed over any section of the path being proportional to the distance between crosses.

It is often desirable to mark in obstacles on a position plot, and this can be done either by typing in their co-ordinates (on the digital system) or merely by holding the sensing linkage over their positions for direct recording.

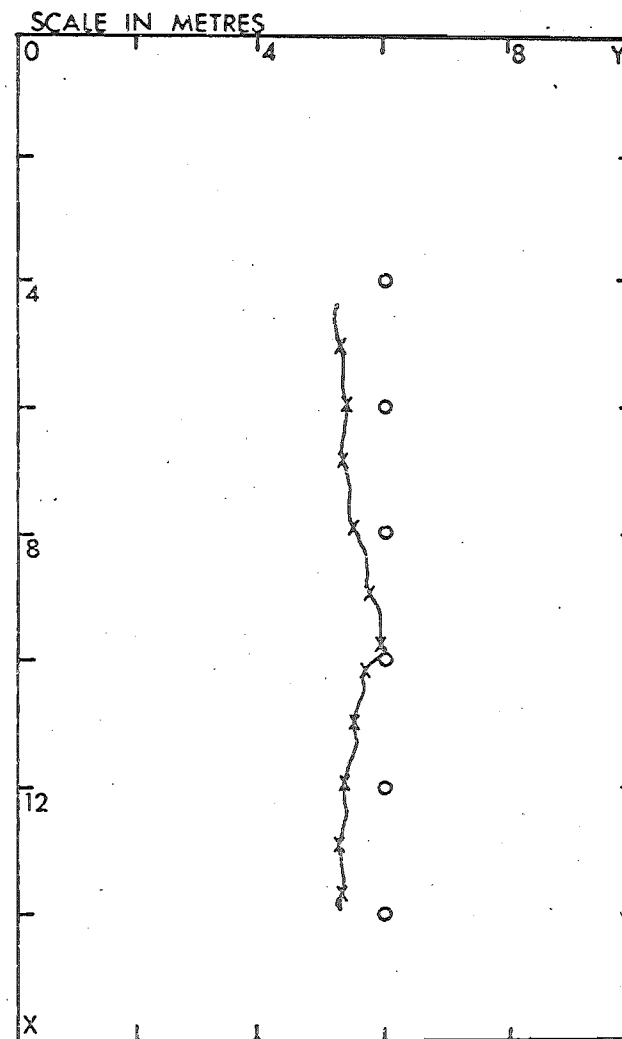
To facilitate this process an option is provided in the computer program so that the computer operator can depress a sense switch and cause the position of the sensing linkage to be monitored on the display screen for as long as the switch remains depressed. No crosses are marked on the plot in this case, and the successively sampled positions are not stored or analysed. This feature is also useful for casual monitoring of a subject's position before and after experimental trials, and the detection of the beginning of a trial. This is especially the case when the T.V. monitor is inoperable due to experiments being carried out in darkness, as is sometimes necessary in investigations of locomotion under reduced visual input.

4.6:2 Distance and Speed Graphs

Using a digital instead of analog computation for monitoring a subject's trajectory permits greater facility in storing and processing the raw data once it is gathered. When developing the data processing aspects of the monitoring system, it was felt desirable to use this flexibility to advantage in providing graphical as well as



(a) Good performance



(b) Poor performance

Fig. 4.12

Typical Position Plots

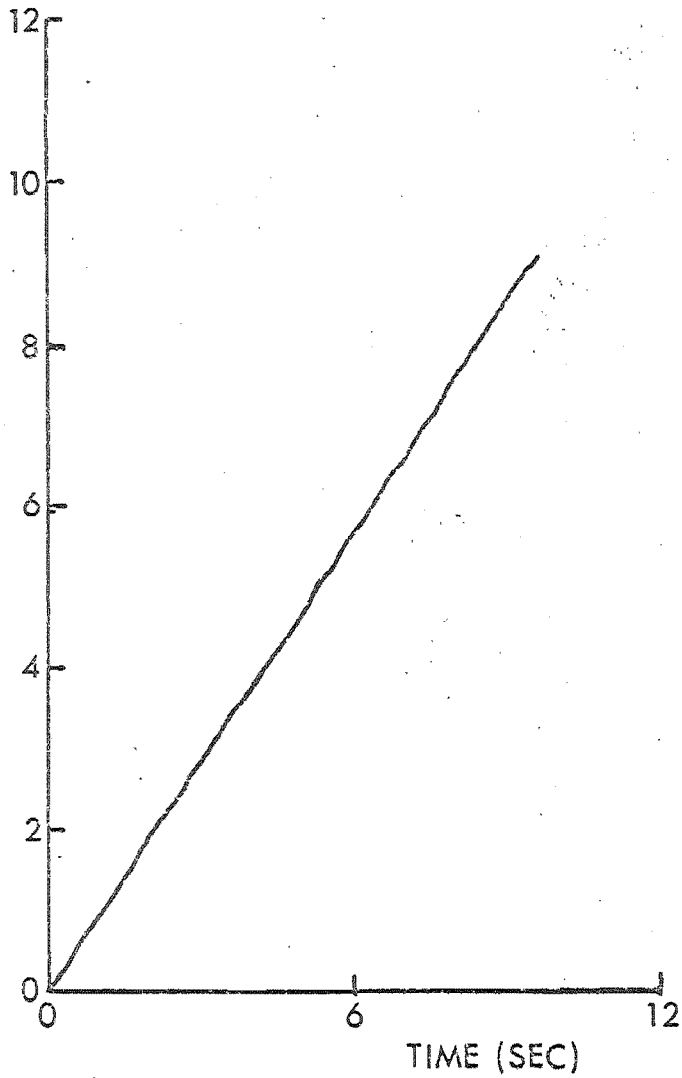
numerical measures of locomotor performance. The value of numerical performance indices alone, while tentatively suggested by experience with the earlier simulation system, had not been convincingly proven, and it was desired to keep other options open.

Thus, apart from producing plots of the subject's trajectory through the environment, at the end of each trial the computer calculates distance travelled and instantaneous velocity magnitude (i.e. speed) for all sample points on the trajectory and plots them against time on the C.R.O. screen. Examples of these graphs are shown in Figures 4.13 and 4.14, plotted for the paths of Figure 4.12.

It has been found that the distance-verses-time curve is very nearly a straight line in all cases of sighted performance, and any deviations from this are quickly apparent from an inspection of the graph (Figure 4.13).

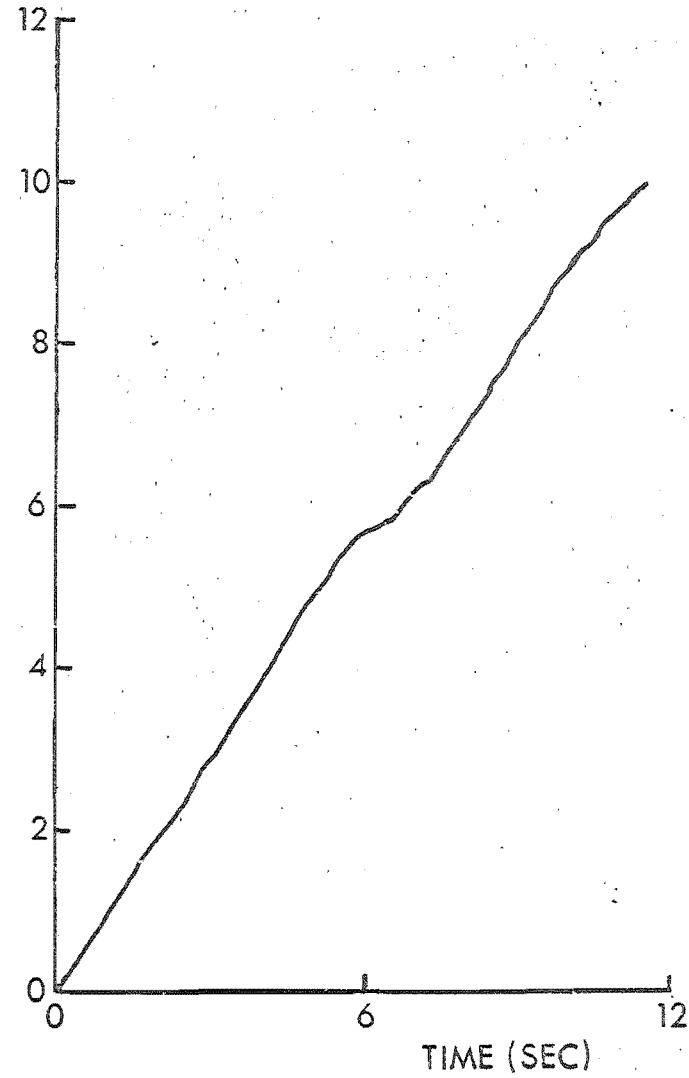
The speed-versus-time graph, as well as indicating the gross variations in speed which are manifested in the distance-time graph, illustrates the "jerkiness" of the subject's gait. The rapid oscillations in the speed graphs reflect the intra-step fluctuations encountered in human locomotion. This is illustrated in the speed plot of Figure 4.15, which was obtained from a subject asked to step in time to a 1.5 Hz pulse train (representing a typical walking cadence (9)), generated by the computer. The pulses were transmitted to the subject through headphones and the instant at which each pulse occurred was encoded by a spike on the speed-versus-time graph. It is clear from this plot that deviations in speed are specifically related to each step, speed reaching a maximum as each foot contacts the ground.

DISTANCE TRAVELLED (M)



(a) Good performance

DISTANCE TRAVELLED (M)

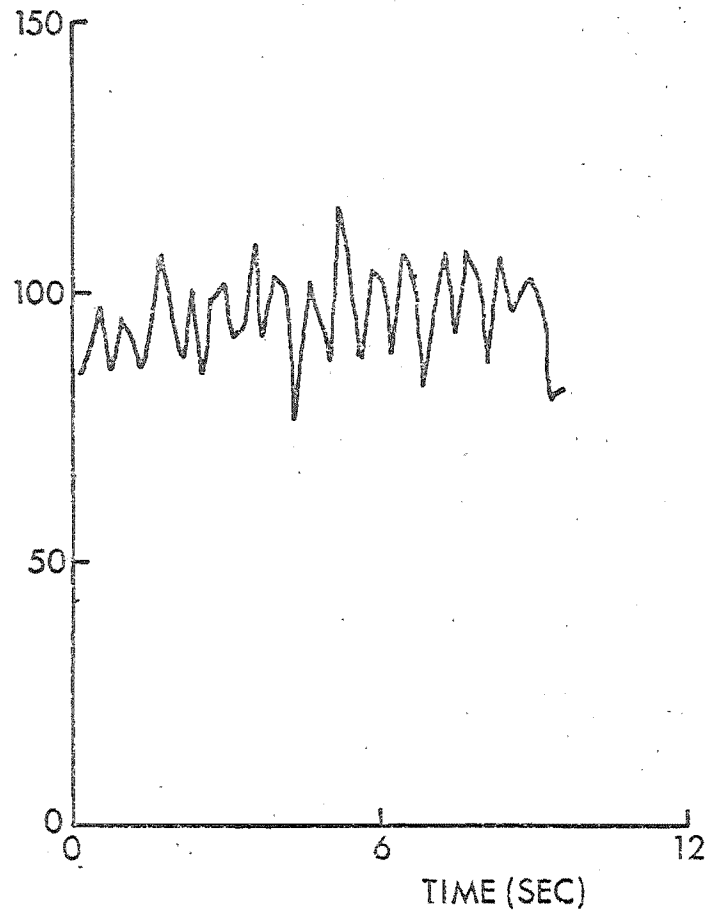


(b) Poor performance

Fig. 4.13

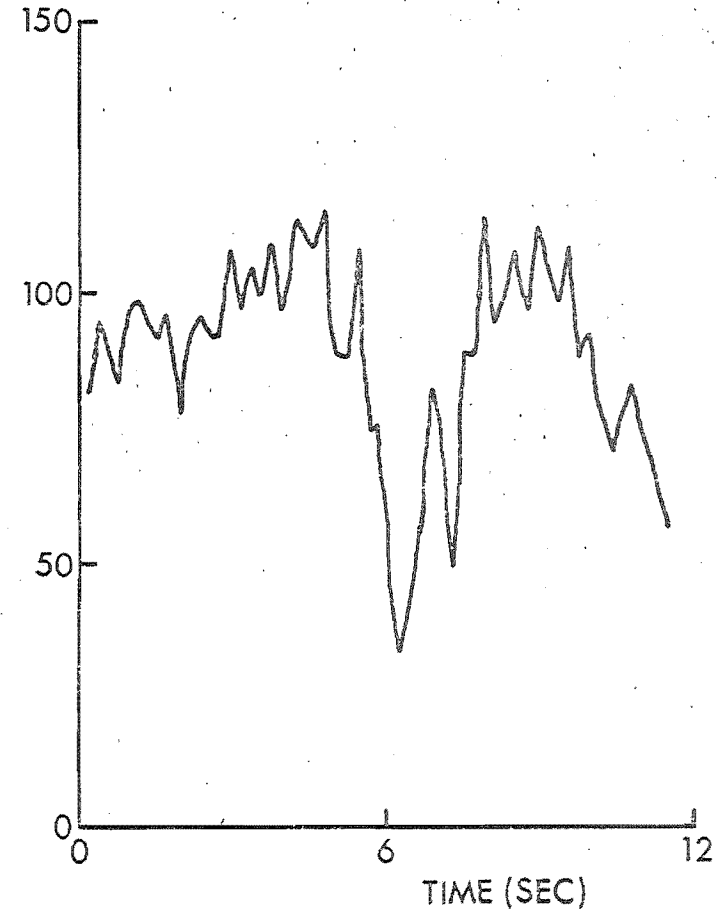
Distance-Vs-Time Graphs Corresponding to Fig. 4.12

SPEED
CM/SEC



(a) Good performance

SPEED
CM/SEC



(b) Poor performance

Fig. 4.14

Speed-Vs-Time Graphs Corresponding to Fig. 4.12

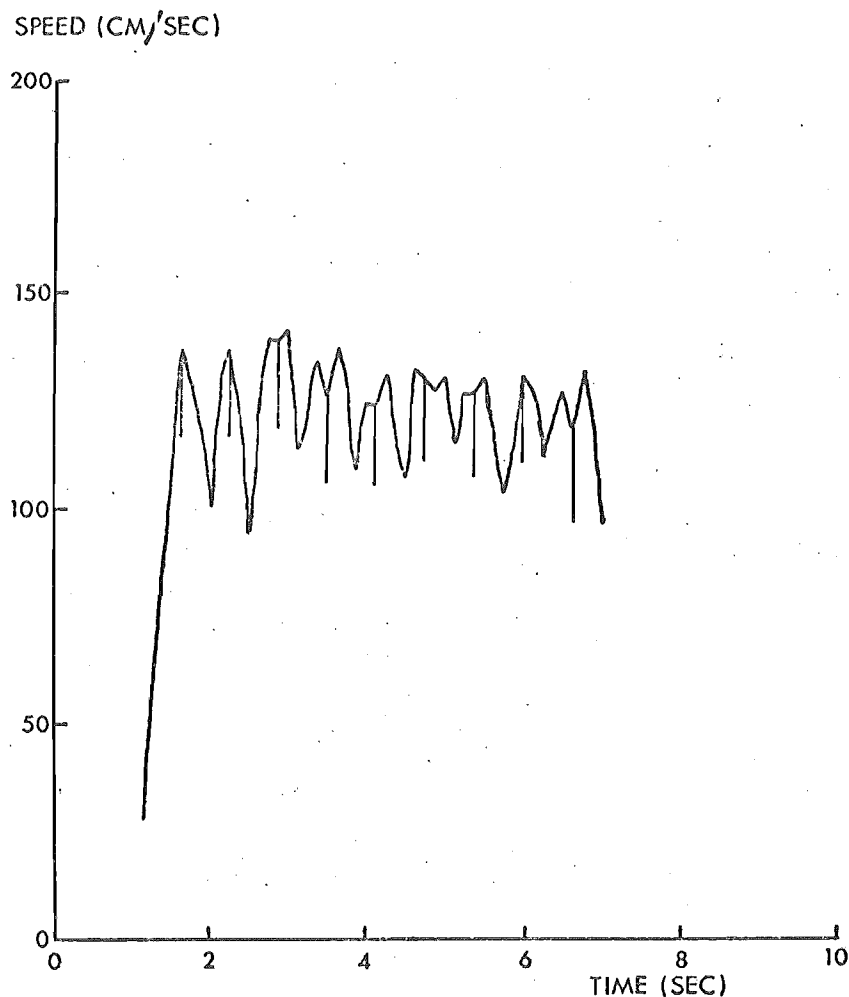


Fig. 4.15

Speed Plot with Footfalls Marked

Too much reliance is not placed on the exactitude of the variations appearing in the speed graphs. The size of the fluctuations inevitably depends upon the sampling rate used and the inherent errors in each position measurement sample. The effects of these factors are analysed in section 4.6:7. These problems could be partially overcome by using a very high sampling rate coupled with digital filtering techniques, but this would involve large storage requirements and would not fully overcome the system's mechanical

limitations. After some experimentation it was found that a sampling rate of 5 Hz was satisfactory for normal purposes, enabled discrimination between smooth and jerky gaits to be made by inspection of the resulting speed plots, and allowed up to 80 seconds of data recording per experimental trial before computer core storage limits were reached.

In sum, the position, distance, and speed plots proved to be useful adjuncts to the numerical measurements subsequently developed for the objective analysis of locomotor performance.

4.6:3 Speed-Devised Performance Indices

The development of numerical indices of locomotor performance followed, in general terms, the earlier experimentation using the hybrid simulation system. In all, some 9 measures of performance are computed by the system, in order to give a reasonably wide selection from which to choose parameters suited to any given purpose.

The first and most obvious numerical characteristic to be computed is Average Speed (AVSP). The distinction between speed and velocity must be noted here - velocity being defined as vector displacement per unit time, whereas speed is total path length (regardless of direction changes) per unit time. Thus in measuring speed, no assumptions need be made about straightness of path or ideal direction of travel. The total path length is thus computed by scalar summing of the individual displacement magnitudes occurring during each sampling interval. This sum is then divided by the elapsed time to produce mean speed.

Care is needed in interpreting the mean speed measure, for while very slow performance would indicate poor mobility, competent travel is likely to be characterised by moderate speed - not necessarily the maximum of which the person is physically capable.

It is desirable to assign numerical descriptors to speed fluctuations. Apart from the marked within-step fluctuations which occur during normal walking, gross overall speed variations can also arise under some conditions (e.g. Figure 4.14(b)), and could indicate poor perceptual motor control.

One means of assessing speed fluctuations is to estimate Average Acceleration (AVAC). In the present system this is performed very simply by dividing the differences between speed estimates for successive sampling intervals by the durations of the time intervals, and taking moduli-yielding an estimate of average acceleration magnitude. This figure is not taken as a precise measure of average acceleration, since the value obtained is dependent upon the sampling interval used (see section 4.6:7). As long as this interval is maintained constant, however, the AVAC value allows a reliable comparison of average acceleration magnitudes between trials and conditions.

An alternative approach, used in the earlier simulation study, is to measure the RMS Deviation from average Speed (RMSDSP) over all samples in an experimental trial. Average Deviation from average Speed (AVDSP) is also computed, but in practice the RMS measure is more often used since it weights large excursions from the mean more heavily than does the AVDAS figure.

While it might appear that the two types of speed fluctuation measures (AVAC and RMSDSP) would detect similar aspects of performance, they actually emphasise different characteristics. Rapid and frequent changes in speed would give rise to large AVAC values. However, if the subject's speed did not remain long at peak and minimum values, RMSDSP would not be correspondingly large. Figure 4.16

shows examples where AVAC and RMSDSP are not highly correlated.

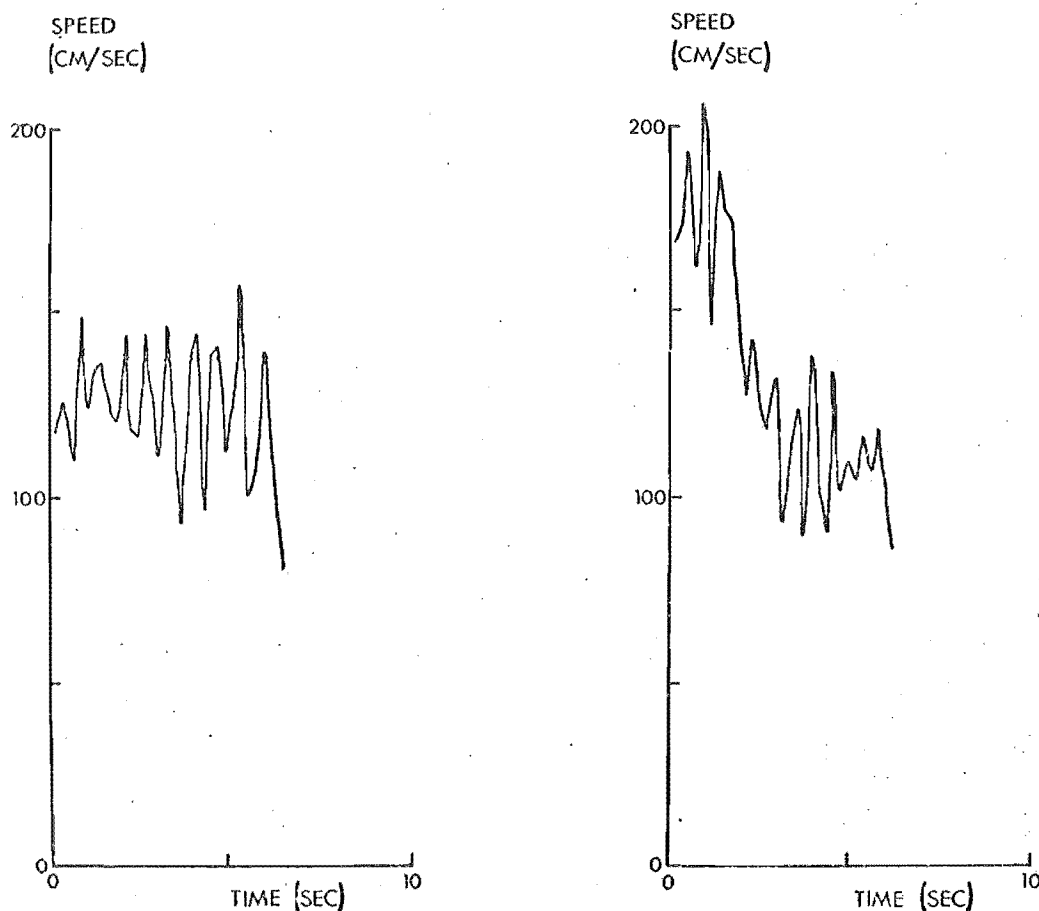


Fig. 4.16

Speed Plots with Similar AVAC but Dissimilar RMSDSP

Retaining both measures makes possible greater precision in performance description.

4.6:4 Path Deviation Indices

The measures described in the preceding section can be regarded as characterising forward body motion; the remaining performance indices describe lateral or side-to-side movements of the

body. These measures are chosen to detect errors in body control which can lead to deviation of the body path from some optimal characteristic.

Two approaches were attempted here, following in the wake of the earlier simulation study. In the first, an "ideal path" was specified before the subject began walking. This is reasonable for many tasks; for example a subject may be positioned 1 metre from a wall and be asked to walk parallel to it. The ideal path is thus a straight line 1 metre from, and parallel to, the wall. Other examples to which this method may be directly applied include the following controlled environment tasks mentioned in section 2.5 wherein mobility was discussed as a control problem:

Task No. (i) - Walking up to a pole from a distance of
several feet;

(iii) - Walking along a row of poles spaced 6 feet apart;

(iv) - Walking between two straight rows of poles spaced
4 feet apart.

Walking up to a pole to pass it at a fixed distance (15), and walking around a circular arrangement of poles, could also be adopted for this type of measurement, although in the latter task the "ideal path" would not be a straight line.

In cases such as these, the RMS and Average Deviation of the subject from the specified Ideal Path (RMSDIP and AVDIP respectively) are measured as indicators of locomotor control accuracy.

Alternatively, if any straight path is acceptable as long as it is parallel to the ideal, a new straight line can be fitted through the subject's actual path by taking the average value of

co-ordinates perpendicular to the original ideal path. RMS and Average Deviation from this Straight Line (RMSDSL and AVDSL) is then computed.

While RMSDIP and AVDIP penalize a subject for any deviation from the specified ideal, the RMSDSL and AVDSL measures are tolerant of a subject who, for example, in a shorelining task, chose to set his own distance from the shoreline.

In practice, the principal measures of path deviations used in studies have been RMSDIP and RMSDSL, for the same reason that RMSDSP is preferred over AVDSP.

It should be mentioned that in computing these path deviation measures, the r.m.s. or averaging process is performed over the samples of a trial representing constant time intervals rather than constant distance intervals. Thus, for example, RMSDIP is the r.m.s. deviation over time from the ideal path, and is different from the r.m.s. deviation computed with respect to distance along the path. This is advantageous in the present circumstance, since a subject who deviates from the correct path and stops or hesitates before returning to it (Figure 4.17a) is penalized more heavily than one who follows the same trajectory through space but corrects the error smoothly and keeps walking (Figure 4.17b).

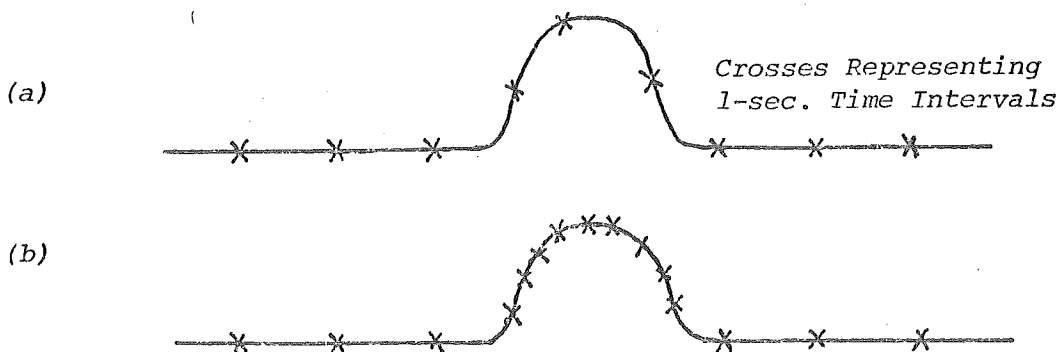


Fig. 4.17
 $RMSDSL(b) > RMSDSL(a)$

4.6:5 Path Curvature

When a subject is asked to walk around a square (Figure 4.18), he will tend to round the corners. There is a sense in which this observed travel may be ideal for the subject even though it does not conform to a geometric ideal.

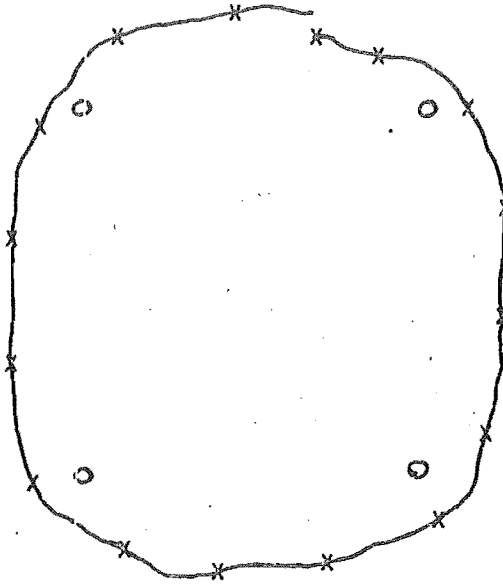


Fig. 4.18

Path of Subject Asked to Circumnavigate a Square

The measure of Surplus Curvature (SCURV) was therefore developed to provide a performance index which is not closely tied to geometrically ideal path shapes. The algorithm sums the incremental angle magnitudes between sample steps (Figure 4.19), giving the total angle turned by the subject's trajectory. From this value the minimum amount of necessary turning is subtracted. For example, in travelling a straight line, 0 radians is the ideal minimum rotation, while 2 π radians is ideal for a circle, square, or any other shape of closed path. After this subtraction, the resulting surplus angle of turn is divided by the total path length to yield "Surplus Curvature" (SCURV) in radians per metre.

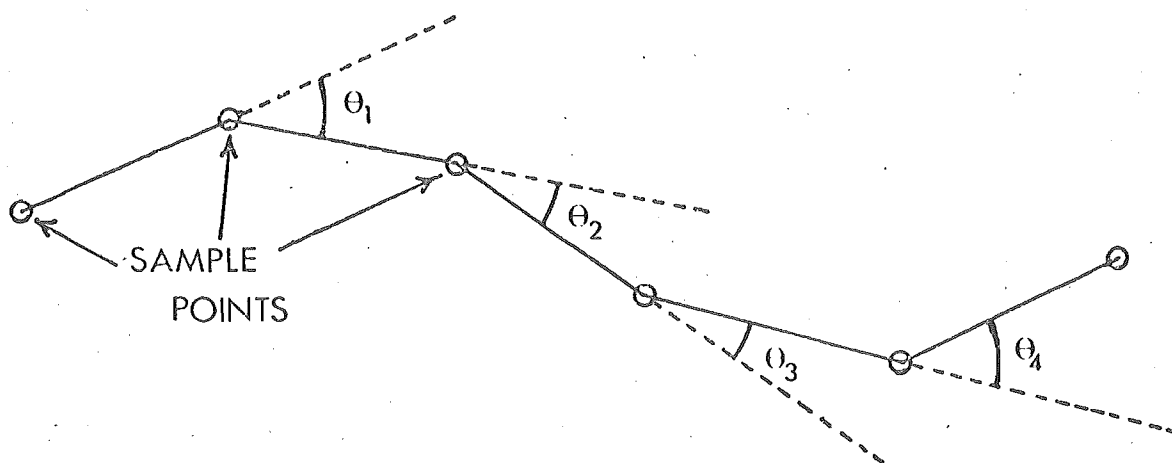


Fig. 4.19
Computation of SCURV

Hence this measure is easily adaptable to a wide range of tasks, although there are certain tasks such as slaloming for which an ideal minimum rotation is not readily definable.

In operation, the ideal minimum rotation is specified on-line by a typed command for whatever task is currently being performed.

4.6:6 Gait Characteristics Vs Path Control

The differences between the path deviation measures (e.g. RMSDIP and RMSDSL) and the curvature measure (SCURV) require emphasis. The former specifically measure the subject's ability to follow some predetermined path with minimum error, and respond to slow as well as fast changes of bodily course. With reference to the hypothetical paths illustrated in Figure 4.20 (a and b), let us assume that the task in each case is to follow the straight line shown dotted. Both paths appear to reflect a similar level of error on the part of the subject in following the "ideal" straight line, but path (b) shows rapid lateral fluctuations (due, for example, to a swaying gait) superimposed on the slower, deliberate course changes made by the

subject.

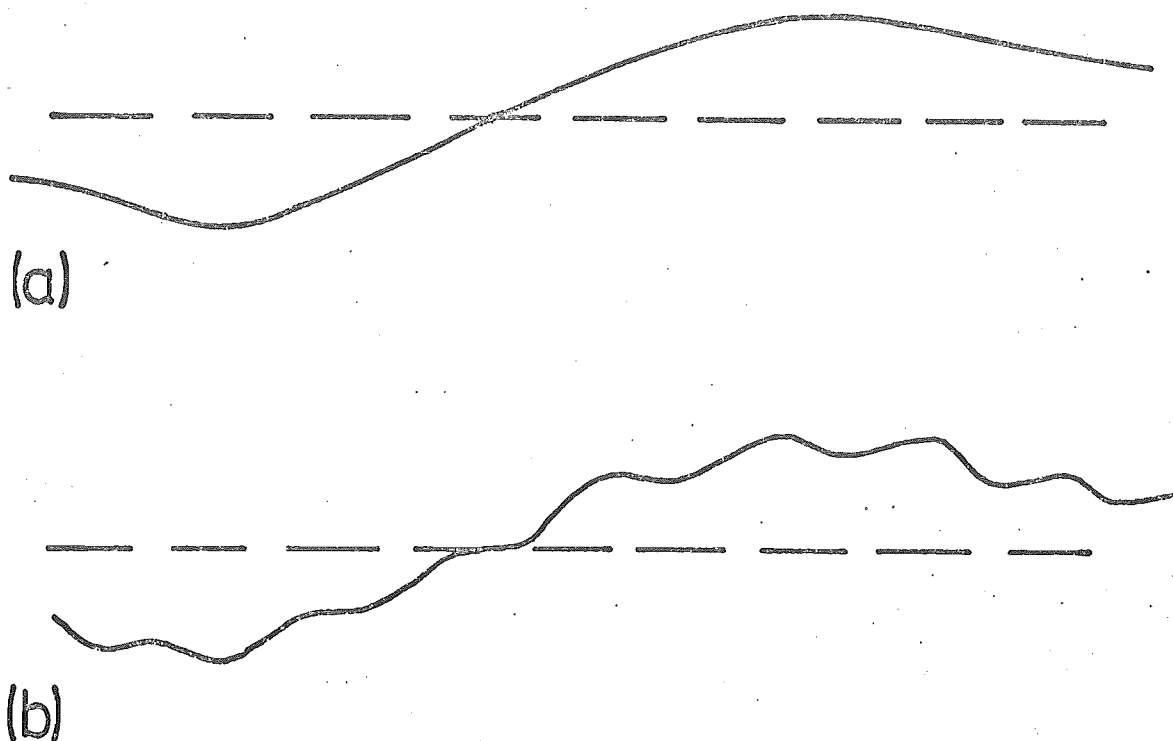


Fig. 4.20

Two Hypothetical Paths

Both plots (a) and (b) would register similar values of RMSDIP and RMSDSL, but path (b) would result in a much higher value of SCURV than (a), because of the rapid oscillations which contain high curvature components.

The two types of measure are not entirely independent, but in general the slower course changes due to bodily path control decisions tend to dominate the r.m.s. deviation measures, while the SCURV measure is sensitive to fast fluctuations such as those due to unusual gait or very poor bodily path control. Because of the effects on gait characteristics of walking at different speeds (Figure 4.10), the SCURV measure usually has a tendency to decrease as speed increases.

By making use of the differing properties of the various performance measures, concerning both forward motion and lateral motion, very subtle distinctions in performance can be recognized.

4.6:7 Effects of Monitoring System Errors and Sampling Rate on Performance Indices

Variation of the sampling rate used when monitoring performance, together with the basic position measurement errors produced by the instrumentation system, must result in errors in the speed and position derived performance indices. Now that the indices themselves have been defined, the effects on them of these errors can be analysed.

To obtain a realistic estimate of the errors, an experiment was conceived in which both sensors and computer algorithms could be tested in terms of their ability to register linear motion at constant speed. The test motion could be produced by attaching the linkage to a wire stretched taut between two pulleys, one of which could be driven by an electric motor at 100 cm/sec.

In attempting to analyse the resulting errors under these conditions, it must be realized that most of the important performance indices - such as AVSP, AVAC, RMSDSP, RMSDSL, and SCURV - require no fixed positional reference. Thus the estimate of maximum absolute positional error (2.7 cm) quoted in section 4.4 is inappropriate for analysing errors in these indices. Instead, an estimate is needed for relative positional error. To obtain such an estimate, it may be assumed that under the above conditions the variation in "sag" error between one sample and the next will be very small, and the quantization errors are, therefore, of principal concern. Relative positional errors of this type will vary between +.4 and -.4 cm in each measuring line, with a rectangular probability distribution (Figure 4.21a). These errors will combine to produce an error in calculated relative position not exceeding their sum (see section 4.4). Assuming the two errors to be independent, their sum will form a random variable with a triangular probability density function (Figure 4.21b).

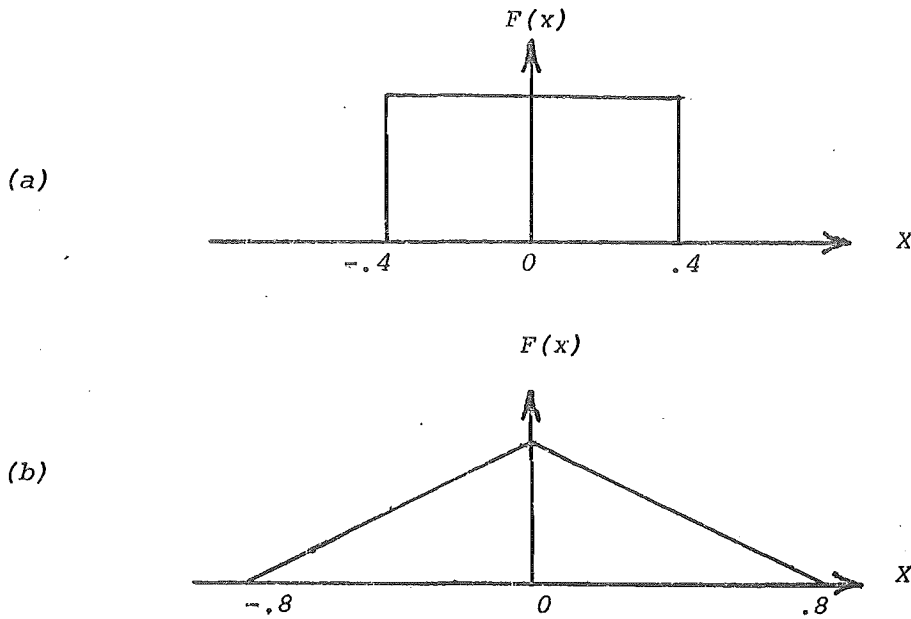


Fig. 4.21

Error Probability Density Functions

To estimate the error in RMSDSL under the above conditions, the r.m.s. value of this type (b) random variable is taken - yielding $0.8/\sqrt{6}$ or 0.33 cm.

Calculation of errors in speed and acceleration indices take account of the algorithms used to compute their values. These are, for the i th sample:

$$V_i = \frac{x_i - x_{i-1}}{T} \quad \dots\dots\dots (4.13)$$

$$a_i = \left| \frac{x_i - 2x_{i-1} + x_{i-2}}{T^2} \right| \quad \dots\dots\dots (4.14)$$

where x_i is the position vector and T is the sampling period.

Hence computation in speed is seen to involve subtraction of two random variables with error distributions as in Figure 4.21b.

Strictly, the resulting error distribution would be a quadratic spline,

but simpler calculations result from approximating each type (b) distribution by a Gaussian, with an r.m.s. value of 0.33 cm. This approximation becomes increasingly accurate as more subtractions or additions of random variables are made, as in calculating speed and acceleration using equations 4.13 and 4.14.

Following this assumption, the speed error distribution would be Gaussian with an r.m.s. value of :

$$\text{r.m.s. error} = \frac{0.33 \times \sqrt{2}}{T} = 2.33 \text{ cm/sec} \quad (T = 0.2 \text{ sec}) \dots (4.15)$$

Thus the expected error in r.m.s. deviation from average speed (RMSDSP) would be 2.33 cm/sec. Expected r.m.s. error in the computed value of average speed (AVSP) over a 5 m distance at approximately 1 m/sec would be less than this value by a factor of \sqrt{n} where n is the number of samples (25). This yields an expected r.m.s. error of $2.3/\sqrt{25}$ or 0.47 cm/sec. Since the ratio of r.m.s. to mean values in a Gaussian distribution is approximately 1.25, the expected mean error in AVSP would be:

$$\text{Expected AVSP error} = .47/1.25 = .38 \text{ cm/sec}$$

The expected error in AVAC under the above conditions can be estimated using equation 4.14 which shows that 6 type (b) error distributions are involved. This yields:

$$\text{Expected AVAC error} = \frac{3.3 \times \sqrt{6}}{1.25T^2} = 16.3 \text{ cm/sec}^2 \dots (4.16)$$

It should be noted that this error increases with the square of the sampling rate.

Computation of SCURV (section 4.6:5) involves combination of four type (b) distributions. A speed of 1 m/sec and a sampling rate of 5 Hz involves a distance between samples of 20 cm. Hence the

expected error in the computed curvature would be:

$$\frac{0.33 \times 4}{1.25 \times 20} = .027 \text{ radians/sample}$$

Since there would be 5 samples/metre;

$$\text{Expected SCURV error} = .027 \times 5 = 0.14 \text{ rad/m.}$$

~ 10°/m

The experiment described above for testing the overall accuracy of the system was performed, and yielded the index values listed in Table 4.1. Also listed in the table are the predicted index errors from the above approximate calculations, and it can be seen that the actual and predicted errors are in reasonable agreement.

TABLE 4.1

Performance Indices for Linear Motion at Constant Speed

<i>Index</i>	<i>Predicted Error</i>	<i>Actual Error</i>
AVSP (cm/s)	0.4	*
RMSDSP (cm/s)	2.3	2.2
AVAC (cm/s ²)	16.3	15.9
RMSDSL (cm)	0.3	0.5
SCURV (rad/m)	0.14	0.18

* Not measurable to required accuracy.

If anything, the errors obtained in the actual tests were likely to be overestimates, since it proved impossible to avoid a small residual transverse oscillation in the moving wire.

The hearing dependence on sampling rate of speed and acceleration errors is evident from equations 4.15 and 4.16. Consequently, doubling the sampling rate would quadruple the error in the acceleration estimate, so too high a sampling rate is clearly undesirable. On the other hand, because subjects might be expected to step at a rate of approximately 1.5 Hz, a sampling rate of at least 3 Hz is desirable if

some estimate is to be made of the subject's intra-step speed fluctuations.

As a compromise, a sampling rate of 5 Hz was chosen.

It will be seen that the errors in the performance indices calculated and observed above, are a good deal lower than the index values obtained for actual mobility performance (see Tables 4.2, 4.3 below). So even the lowest values of path and speed deviations for good, sighted performance appear to be well above the measurement threshold of the system. In particular, it will be seen that the lowest value of RMSDSL (3.2 cm) obtained from subjects attempting to follow a straight path (Table 4.3) is at least six times the observed threshold (Table 4.1) of 0.5 cm.

4.7 VALIDATION OF PERFORMANCE INDICES.

4.7:1 Introduction

It was not obvious at the outset whether any differences at all would be measurable between performance levels reached by persons using different forms and amounts of sensory inputs in the controlled environment tasks. Would sighted performance be distinguishable from that of a competent mobility aid user? One opinion was that it would not. Would the system be too inaccurate to make fine discriminations between performance levels? Would sighted performance even be distinguishable from performance under blindfold without artificial aids? Would the type of task used be so trivial and the human mobility system so stable that performance, even if it could be measured with millimetric accuracy, would be totally unaffected by changes in sensory input?

In order to commence answering some of these questions, the experiments outlined below were conducted.

4.7:2 Demonstrations of Mobility Performance

In the first set of demonstrations, three tasks were chosen to represent some of the common characteristics of mobility. The purpose was to assess the typical numerical values obtained by normal, sighted subjects, and the variability of these measures from trial to trial, and across subjects. In experimental settings, these conditions typically provide the baseline against which the conditions of non-optimal perceptual control information are compared. In the second set of demonstrations, the perceptual information for accurate locomotor control was impaired by requiring subjects to perform with degraded vision, or by auditory control. The numerical measures were shown to be capable of differentiating these performance conditions from the normally sighted condition.

4.7:3 Visual Control Tasks

In the first task, subjects were asked to walk towards a target 10 m distant. In the second task, subjects were required to walk in a slalom fashion around 6 poles, placed 2 m apart, and to keep at approximately arm's length from the poles. In the third task, subjects were required to walk around 8 poles, arranged in a circle 4 m in diameter, again staying at arm's length from them. The tasks chosen thus required steady locomotor control (straight line task), rapid path alterations (slalom) and gradual path changes (circle) in response to visual, spatial information.

Six subjects performed each task ten times in different orders. Subjects were asked to walk as normally as possible; however, early experience indicated that there was considerable variability in inter-

preting this instruction - some subjects travelling at a pace close to running. Accordingly, some control over speed was obtained by requiring subjects to walk in time to a metronome set to 1.5 Hz, a typical walking cadence.

The numerical measures are shown in Table 4.2. The RMSDIP and RMSDSL measures are strictly applicable only to straight line travel, but were also computed for the slalom to indicate that these measures are sensitive to gross path changes.

The standard deviations are reasonably small both within and across subjects, indicating consistency of performance, although greater variability could be expected if the stepping rate was not set by a metronome. The magnitude of the measure would depend on the nature and positioning of the mechanical linkage as different parts of the body move in different patterns (9). The previous conditions were repeated for a further six subjects using a linkage attached to the top of a small adjustable helmet worn on the head, in the expectation that this linkage would register less body sway than one mounted on a pole some distance over the subject's head.

The results are shown in Table 4.3. It can be seen that while speeds were higher for these subjects than for the previous six, most measures of path and speed variability were reduced, with surplus curvature in particular being affected.

It would thus appear that head mounting can result in a lowering in the basic deviation indices and could increase the sensitivity of experimental conditions. However, this is done at the cost of introducing detectable forces at the subject's head. Whereas a resultant force of 50 g was required with back mounting before its

TABLE 4.2

Sighted Performance : Pole Mounting

	STRAIGHT LINE			SLALOM			CIRCLE		
	Mean	σ_1^*	σ_2	Mean	σ_1	σ_2	Mean	σ_1	σ_2
AVSP (cm/s)	95.5	(3.0)	(7.4)	78.4	(1.75)	(2.4)	91.1	(2.8)	(6.2)
AVAC (cm/s ²)	57.8	(9.4)	(11.7)	58.6	(6.7)	(12.6)	59.5	(2.8)	(10.8)
RMSDAS (cm/s)	9.8	(1.2)	(1.9)	11.4	(1.0)	(2.0)	9.8	(1.2)	(1.6)
RMSDIP (cm)	7.5	(2.5)	(2.0)	47.7	(2.3)	(7.4)	-	-	-
RMSDSL (cm)	4.0	(0.7)	(0.7)	47.0	(2.2)	(7.3)	-	-	-
SCURV (rad/m)	.798	(.114)	(.169)	1.664	(.139)	(.322)	.870	(.117)	(.213)

* σ_1 = mean standard deviation of within subject variability

σ_2 = standard deviation of mean scores across subjects

TABLE 4.3

Sighted Performance : Head Mounting

	STRAIGHT LINE	SLALOM	CIRCLE
AVSP (cm/s)	106.9	83.7	102.7
AVAC (cm/s ²)	39.8	40.6	41.9
RMSDAS (cm/s)	7.6	8.5	7.5
RMSDIP (cm)	7.0	57.6	-
RMSDSL (cm)	3.2	56.8	-
SCURV (rad/m)	.359	1.101	.416

direction could be sensed (section 4.3:2) only 10 g was found to be required with head mounting. An additional disadvantage is that if tall obstacles are introduced in an experimental setting, there is some danger of these snagging the measuring lines. On the other hand, the forces on the subject's head, while above threshold, are by no means obvious, nor do they result in fatigue when head mounting is used. Also, the head mount is easier to take on and off than the back mount. Finally, the position bias possible with head mounting can usually be discounted as a factor in experiments by the use of appropriate control conditions. However, if this form of bias must be reduced to an absolute minimum, then back mounting is preferable.

4.7:4 Locomotor Control with Degraded Perceptual Input

Finally, an experiment was performed to test the ability of the computer-coupled monitoring system to discriminate between good and poor performance in a given task when the perceptual control information was degraded. Six subjects were used, with head mounting.

The task of walking straight towards a target was investigated under three different conditions of sensory input: sighted performance and two conditions expected to be more difficult - degraded vision and auditory control.

In the normal vision condition, a pole at a distance of 10 m was the target of approach. In the degraded vision condition, a light was mounted at a height of 1.6 m on the pole, and the room was darkened out. A facemask of diffusing glass reduced the subject's perception of the target light to a blur extending over 30° to 40° of the visual field. In the auditory condition, the light was replaced by the metronome (used in all cases to control the rate of walking) mounted at the same height and set to 1.5 Hz. The subject was blindfolded and instructed to walk towards the sound source. Every subject again performed each task 10 times with a different order of conditions.

The results are presented in Table 4.4 along with indications of their statistical significance. Average speed was down for the conditions of degraded perceptual input, while the measures of deviations in speed and path trajectory increased. Significant differences between normal visual control and degraded vision or auditory control were noted for all measures except AVAC and SCURV. This confirmed the expectation that conditions of degraded input would result in performance measurably different from normal, visual control. From the standpoint of perceptual-motor control, any increase in such deviations must be regarded as indicating poorer performance. The

TABLE 4.4

Locomotor Control with Visual, Auditory and
Degraded Visual Control Information

	NORMAL VISION	AUDITORY CONTROL	DEGRADED VISION
AVSP (cm/s)	113.5	102.8*	103.2**
AVAC (cm/s ²)	32.5	35.8	35.9
RMSDAS (cm/s)	7.2	10.9*	10.2**
RMSDIP (cm)	6.6	21.5*	19.7***
RMSDSL (cm)	3.4	9.7***	8.4***
SCURV (rad/m)	.377	.429	.499

For no measures were there significant differences between Auditory Control and Degraded Vision. Statistical differences between either of these and Normal Vision ($t(df=5)$, 2-tailed test) are noted as follows:

* $P \leq .05$

** $P \leq .02$

*** $P \leq .01$

reduction of speed for the conditions of degraded input could also indicate a greater difficulty in these conditions (however, see above discussion on Average Speed). From these results, therefore, it seems fair to conclude that the monitoring system meets the prime requirement for the study of mobility and perceptual-motor performance, namely, that it can detect subtle losses of motor control.

4.8 DISCRIMINATION BETWEEN BLIND (AIDED) AND SIGHTED PERFORMANCE.

Having shown that subtle variations in locomotor control performance could be detected by the system and associated measures, it remained to discover whether the performance of users of available electronic sensory aids is measurably different from that of sighted persons.

An experiment was conducted using a mobility aid (Sonicguide) whose display (16) was comparatively rich in information. The subject in this case, as the inventor of the device, was extremely familiar with it, had accumulated extensive experience in using it under blind-fold, and was kind enough to offer his services in the investigation.

A task commonly used in Sonicguide training - that of shorelining a straight row of poles at a constant distance - was used. The poles were spaced 1 metre apart over a total distance of some 10 metres. Because the poles were approximately 2.3 metres tall, back mounting of the sensing linkage was used to avoid snapping. The mount was of an improved design which was calculated to reduce excess swaying at the sensing linkages, and took the form of a light pole attached to a pack frame mounted on the subject's shoulders and back.

The subject was placed 1 metre from the shoreline at the beginning of each trial, and asked to maintain a path parallel to the

poles. The 1.5 Hz metronome was again used to control walking cadence. Ten trials were performed under each of two conditions - normally-sighted and blindfolded (with Sonicguide).

Results (Table 4.5) showed that the difference in performance between the two conditions was easily measurable, particularly in terms of RMSDIP and RMSDSL, which demonstrated a marked loss in body control under the artificially aided condition. At the request of the subject, two further trials were performed using the Sonicguide but without the metronome - the subject being free to set his own walking speed. Although an increase in speed, and a reduction in path deviation occurred (Table 4.5), performance in terms of the bodily control indices (RMSDIP and RMSDSL) was still well below sighted levels.

TABLE 4.5
Shorelining Task

<i>Condition Index</i>	<i>Sighted (10 Trials)</i>	<i>Sonicguide (10 Trials)</i>	<i>Sonicguide (Natural Speed 2 Trials)</i>	<i>Units</i>
AVSP	99.8 (6.2)*	87.2 (6.2)	102.1	cm/s
AVAC	57.1 (10.3)	36.2 (4.1)	42.0	cm/s
RMSDAS	9.1 (1.4)	6.6 (.8)	8.4	cm/s
RMSDIP	8.5 (3.7)	43.7 (28.3)	22.4	cm
RMSDSL	4.3 (1.5)	14.9 (5.4)	9.4	cm
SCURV	.570 (.046)	.804 (.128)	.626	rad/m

* Standard Deviation (σ_{n-1})

It was concluded that little difficulty was likely to be encountered in discriminating between sighted performance in controlled environment tasks, and the level of performance achievable with presently available sensory aids.

4.9 GENERAL DISCUSSION.

The measuring system enables a quantitative assessment of the ability of subjects to use restricted perceptual information to control their body movements, and should allow assessment of the usefulness of electronic sensing aids for blind mobility. The indices chosen were felt to be suitable for these purposes although for other purposes other indices could be derived. However, the measures chosen are not entirely arbitrary. Measures of speed and path deviations, particularly when applied to studies of normal visual control, quantify fundamental characteristics of human gait. The system and measures may therefore be useful for other types of study; one application already exploited is the investigation of the deterioration in locomotor performance caused by the intake of alcohol (16). A further possible use of the system may be to define normal gait so that the use of limb prosthetics can be assessed.

REFERENCES

- (1) Mills, A.W.; "Toward an Empirical Theory of Mobility".
Research Note, Dept. of Psychology, Tufts University, Massachusetts.
- (2) Russell, L; "Special Instrumentation for the Evaluation of Mobility Aids". Final Report for Sensory Aids Evaluation and Development Center, M.I.T., Oct. 1965.
- (3) Dupress, J.K.; "Sensory Aids Evaluation : Procedures and Instrumentation". Proc. Int. Conf. on Sensory Devices for the Blind, R. Dufton, Ed., London : St. Dunstan's, 1967, pp 293-7.
- (4) Baecker, M.R.; "Computer Simulation of Mobility Aids : A Feasibility Study". AFB Research Bulletin, 1968, 16, 141-205.
- (5) Nye, P.W., Bliss, J.C.; "Sensory Aids for the Blind : A Challenging Problem with Lessons for the Future". Proc. IEEE, 1966, 58, 12, 1878-98.
- (6) Mann, R.W.; "The Evaluation and Simulation of Mobility Aids for the Blind". AFB Research Bulletin, Oct. 1965, 1-62.
- (7) Cheng, I., Koozekanani, Fatehi; "A Simple Computer-Television System for Gait Analysis". IEEE Trans. BME, 1975, BME - 22, 3, 259-260.
- (8) Nye, P.W. (Ed.); "Selected Research Development, and Organizational Needs to Aid the Visually Impaired". Committee on the Interplay of Engineering with Biology and Medicine : Subcommittee on Sensory Aids. Nat. Acad. Engineering, 1973.
- (9) Contini, R., Gage, H., Drillis, R.; "Human Gait Characteristics". Biomechanics and Related Topics - Proceedings of a Symposium held in Glasgow, Sept. 1965. R.M. Kenedi Ed., Pergamon Press, Oxford, 1965.
- (10) Inman, V.T.; "Conservation of Energy in Ambulation". Bulletin of Prosthetics Research, 1968, B.P.R., 10 - 9, 26 - 35.
- (11) Strelow, E.R., Brabyn, J.A., Clark, G.R.S.; "Apparatus for Measuring and Recording Path, Velocity, and Direction Characteristics of Human Locomotion". Behaviour Research Methods and Instrumentation, 1976, 8, 5, 442-446.
- (12) Brabyn, J.A., Strelow, E.R.; "Computer-Analysed Measures of Characteristics of Human Locomotion and Mobility". Behaviour Research Methods and Instrumentation, 1977, 9, 5, 456-462.

- (13) Brabyn, J.A., Sirisena, H.R., Clark, G.R.S.; "Instrumentation System for Blind Mobility Aid Simulation and Evaluation". Submitted IEEE Trans. BME
- (14) Kay, L., Bui, S.T., Brabyn, J.A., Strelow, E.R.; "Single Object Sensor : A Simplified Binaural Mobility Aid". Journal of Visual Impairment and Blindness, 1977, 210-213.
- (15) Kay, L.; "Towards Objective Mobility Evaluation : Some Thoughts on a Theory". AFB Monograph, 1974.
- (16) Kay, L.; "A Sonar Aid to Enhance Spatial Perception of the Blind: Engineering and Evaluation". The Radio and Electronic Engineer, 1974, 44, 11, 605-627.
- (17) Gregson, R.A.M., Smith, D.A.R., Strelow, E.R., Brabyn, J.A.; "Acute Effects of Alcohol on Measures of Walking Performance". Applied Psychological Measurement, In Press.

A THIRD STEP : AID SIMULATION AND EVALUATION WITH REAL LOCOMOTION TASKS

5.1 INTRODUCTION.

Development and combination of the performance measurement and simulation techniques already described appeared to offer the possibility of simultaneous simulation and evaluation of blind mobility aids under conditions of real locomotion in a controlled environment. The principal obstacle to previous attempts - namely the problem of instrumentation of a moving object - had been removed by the development of a monitoring system of surprising simplicity and accuracy. Further developments - outlined in the present chapter - would still be needed, but conceptually at least, simulation of aids using simple auditory displays appeared to be feasible.

In the monitoring system already described, only 16 ms of computer time was required for calculation and display of subject position at each sample point. At a sampling rate of, say, 10 Hz, — the minimum considered necessary for any real-time simulation, approximately 84 ms per sampling interval would be available for other computations associated with simulating an auditory display.

Mention should be made here of the available computing facilities, since their nature was more of a constraining influence in the simulation system than in the work of previous chapters. The digital computer, an EAI 640, had 16 k words (16-bit) of core and a cycle time of 1.6 microseconds. Although this was slow and small by contemporary standards, and no floating point processor was available, the presence of the EAI 580 analog computer, with an EAI 592 interface, compensated

for this disadvantage to some extent. This hybrid computing facility, used in the previous simulation system, was convenient for interfacing analog (audio) signals with the simulation algorithms.

5.2 PREVIOUS AID SIMULATION PROPOSALS.

Various proposals have been put forward by other authors for simulation of mobility aids in a real environment. The desirability of such simulation systems has, of course, been repeatedly expressed (1-7), and the advantages and disadvantages of simulating aids were discussed in chapter 3 above.

Perhaps the most detailed proposal in the literature was that put forward by Baecker (5), who concluded that for reasonable standards in calculation accuracy, and if the environment were required to be natural, simulation on available digital computers (1968) would fail by 2 orders of magnitude to achieve the 1,000 "pencil-beam" calculations per second required for his proposal. He therefore advanced arguments for an independent scanner/rangefinder coupled to a digital processor, a solution which would, it was freely admitted, be complex.

Another proposal was made by Mills (6,7), who made an attempt to solve the tracking problem, but attention was to be focussed on a 12' x 12' room (probably reflecting in part the limitations of the proposed monitoring system), which would not have allowed any reasonable length of travel path for the subject.

These proposals appeared to represent opposite extremes of ambition while both were hampered by lack of instrumentation facilities. Apart from this latter problem, the form of such a simulation would, as will become apparent, be heavily dependent on the

types of mobility aid displays it is desired to investigate.

5.3 EFFECTS OF POSSIBLE DISPLAY PARAMETERS ON SIMULATION TECHNIQUES.

The monitoring system as developed was well suited to dealing with the environment in plan view. This mode of display is inherent in all sonar aids, which give direct range and azimuth information about objects in the environment.

The alternative mode of display, used by light imaging systems such as TV-tactile display systems, present an elevation-type view of the environment. Such systems require a high information content in order to allow accurate positional judgements to be made, since range cues are implicit rather than explicit in the display. This matter is discussed in section 8.2. Simulation of such high-information, "elevation-view" systems would be very complex. The proposal of Baecker (5), for example, required two monitoring systems, each measuring the position in 3 dimensions of either end of a hand-held probe manipulated by the subject.

It was decided to concentrate on the "plan view" mode in the simulations. This was well suited to the existing monitoring system and to most present mobility aids (including the Sonic Glasses and the Single Object Sensor, the devices upon which attention was initially centred), and permitted the use of simpler algorithms than would the general case mentioned above.

Requirements for the simulation of the Single Object Sensor would be relatively few. The binaural display of this device (8) is a pulse train, and presents the position of the nearest object within its beam. Range is encoded as the time delay between pulse or

"clicks", while azimuth is indicated by inter-aural amplitude difference (I.A.D.). Simulation of such a display would require control over pulse-rate and I.A.D. only.

The Sonic Glasses, or Binaural Sensory Aid, described in chapter 3, encodes range in the frequency domain, allowing perception of multiple targets (9). In simulating a device of this general type, it would be necessary to control frequency and inter-aural amplitude for each target displayed. Accurate simulation of use in a complex environment would involve control over timbre of signals due to objects with differing ultrasonic target characteristics, and was not initially contemplated.

In simulations of any display of the above or related types, control over signal amplitude would be desirable whether I.A.D. were present or not, since even where amplitude was not a cue, the signal would need to be reduced to zero amplitude when objects were outside the beam of the simulated device.

Thus the number of parameters to be controlled, at least for simulations involving simple environments, was not excessive. It appeared that a separate voltage-controlled oscillator with selectable waveforms would be needed for each target present in the display at any given time. Each oscillator would require individual control over the volume of its signal applied to each ear of the subject. Such a system should allow a wide range of simple device characteristics to be simulated, and further refinements such as production of inter-aural time differences (I.T.D.) could be added later if desired.

5.4 SYSTEM REQUIREMENTS.

Extension of the existing monitoring system to allow simulation of mobility aid displays required modifications to both hardware and software. In terms of the former, it was necessary to devise some method of monitoring the subject's orientation as well as his position, to inform the computer of the direction in which it should be searching for objects. Other hardware requirements included the provision of suitable auditory signal generation apparatus, and arrangements for the signals to be presented to the subject via headphones.

On the software side, the existing program had to be completely remodelled to allow the insertion of routines for aid simulation. The major limitation here was computation speed, as it was deemed necessary to sample the subject's position and update the display at intervals of less than 100 msec if at all possible. For a subject travelling at 1 m/sec this would result in a distance of 10 cm being covered before the display was updated - this was considered the maximum allowable lag. During this 100 msec, the computer had to calculate the subject's position and head orientation, plot his path on the C.R.O. screen, search the region in front of him for obstacles (the positions of which had been previously stored), calculate the range and azimuth of those within the simulated "beam", calculate appropriate frequencies and amplitudes according to the device characteristics, and update the auditory display accordingly.

It was also desirable for the system to be as flexible as possible in terms of ease of changing environmental and display characteristics, to maximise operator convenience so that the computer operator need not have special skills, and to minimise processing aid data handling time between experimental trials. These requirements

were the more important since a dedicated computer was not available. It was necessary to make the most efficient possible use of computer bookings (1-2 hours each), which often had to be made several days in advance.

5.5 SYSTEM DESCRIPTION.

5.5:1 General

An overall block diagram of the system as completed appears in Figure 5.1, and a simplified flow chart (Figure 5.2) illustrates the sequence of system operation. The areas of these diagrams enclosed within dotted lines constitute the additions to the existing system necessary to allow aid simulation. These modifications are briefly described below.

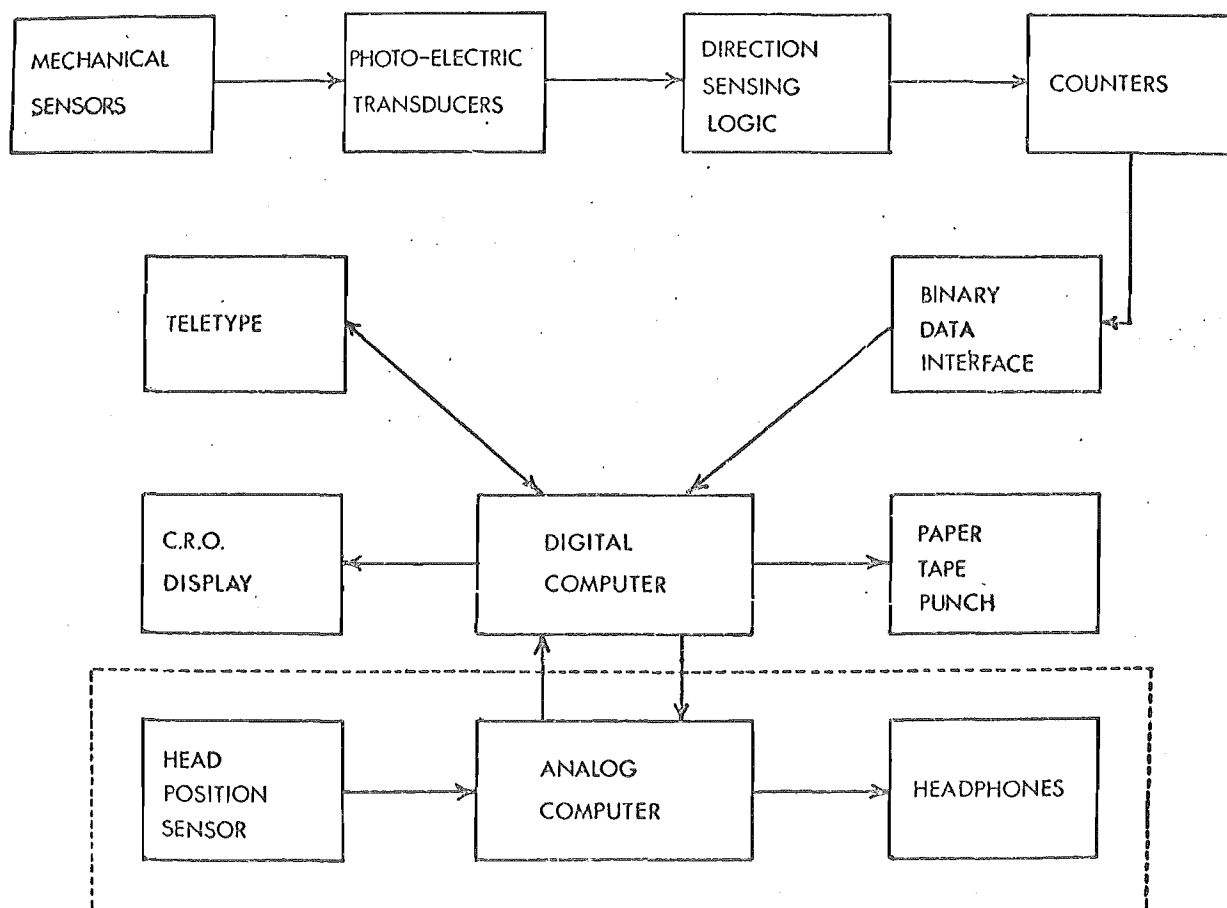


Fig. 5.1

System Block Diagram

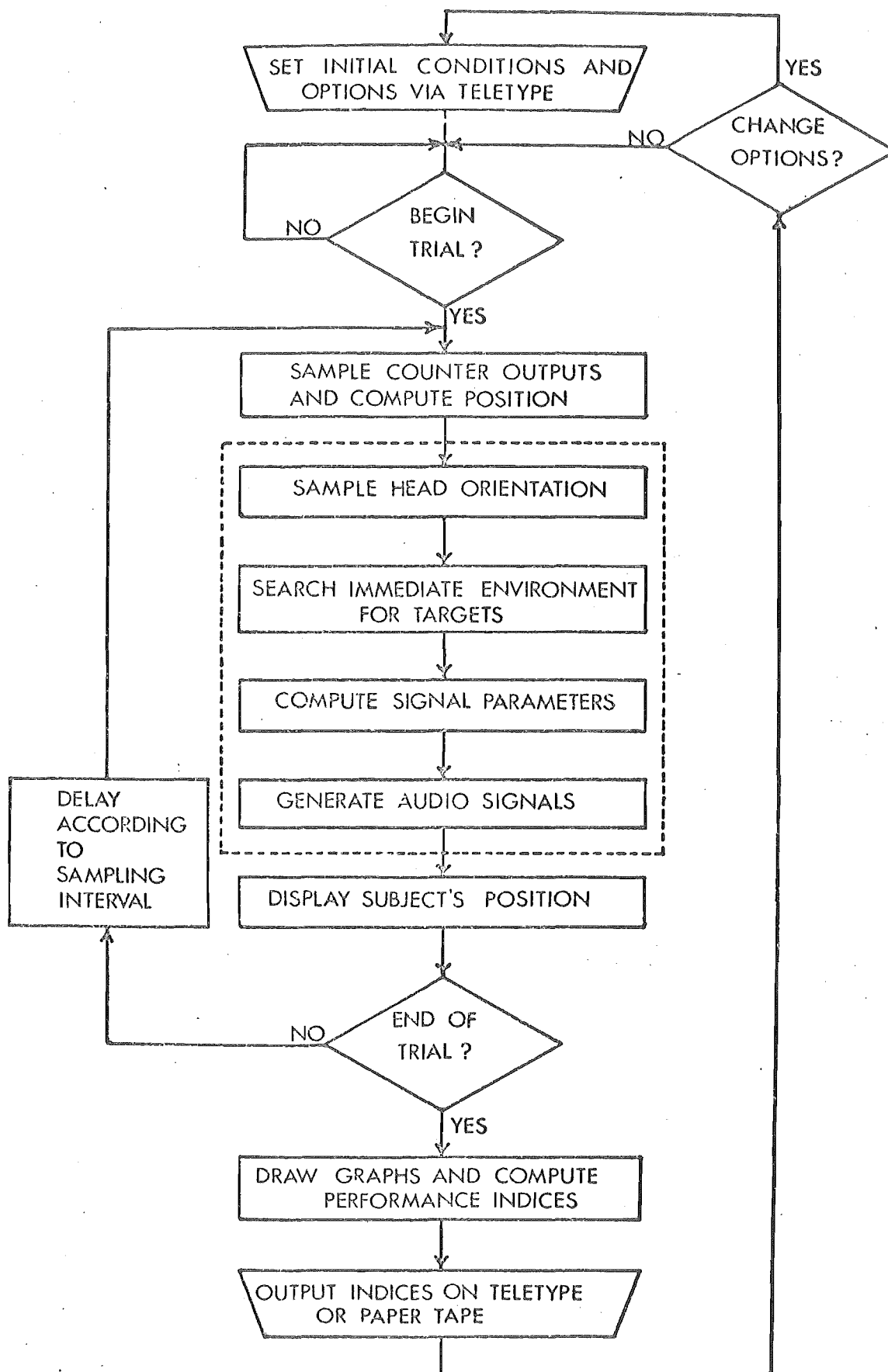


Fig. 5.2
Software Flow Chart

5.5:2 Monitoring Subject Orientation

To simulate head-mounted aids it was clearly necessary to monitor the orientation of the subject's head relative to the fixed co-ordinates of the environment. The system adopted was the result of some experimentation with various configurations, and is illustrated in Figure 5.3. The principle used here is to measure head orientation relative to the passive sensing line, and then calculate by trigonometry the actual orientation relative to the x-axis according to the current position of the sensing linkage in the room (Figure 5.4).

The angle subtended by the subject's head direction with the passive sensing line is measured by fixing the sensing linkage to the shaft of a low friction 360° potentiometer mounted atop the headphones worn by the subject. The passive sensing line is connected to the potentiometer shaft via a light aluminium strip 17.5 cm in length. This allows the tensioned line to exert sufficient leverage on the shaft to overcome potentiometer friction. Alignment error was measured at less than one degree. The other two (active) sensing lines are connected to the axis of the potentiometer shaft via short brass strips on a low friction pivot, and exert no torque on the shaft.

The potentiometer is connected across the 0-10V supply of the analog computer, allowing adequate sensitivity in angular measurement (30 mV/degree). The wiper is connected to the input of one of the analog computer's A-D convertors for convenient sampling by the digital machine.

With reference to Figure 5.4, if θ_t is the subject's head orientation relative to the passive sensing line and (x,y) and (x_D, y_D) are the respective positions of the subject and the passive sensing drum, the absolute orientation of the subject's head relative to the

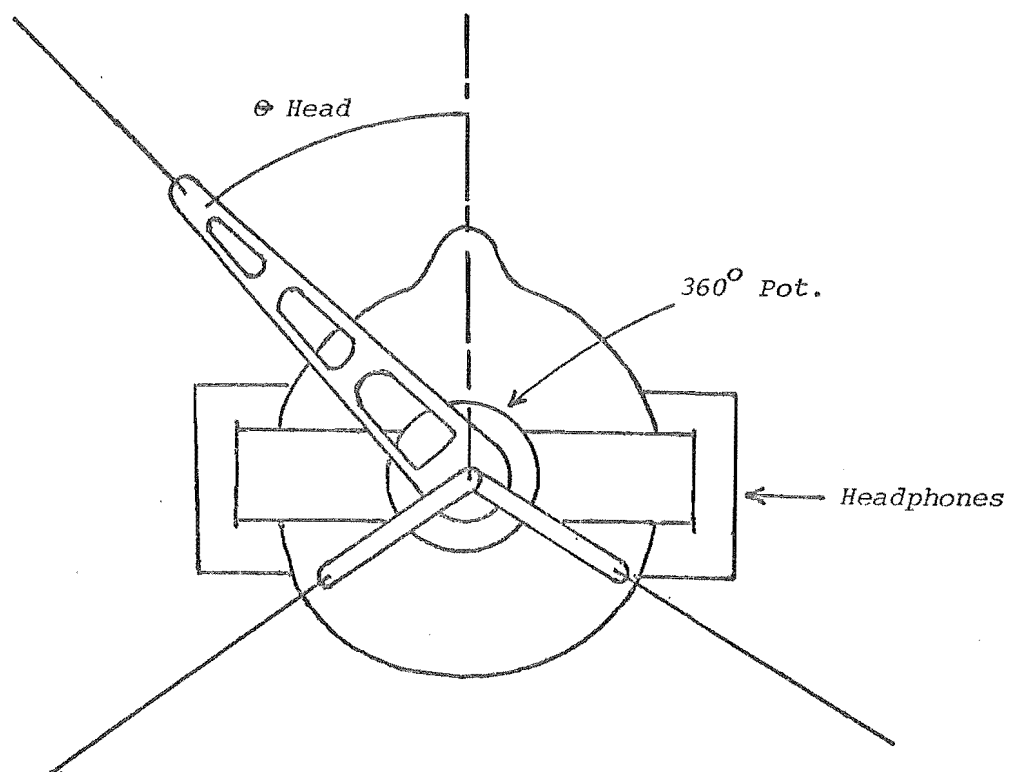


Fig. 5.3
Head Position Sensing

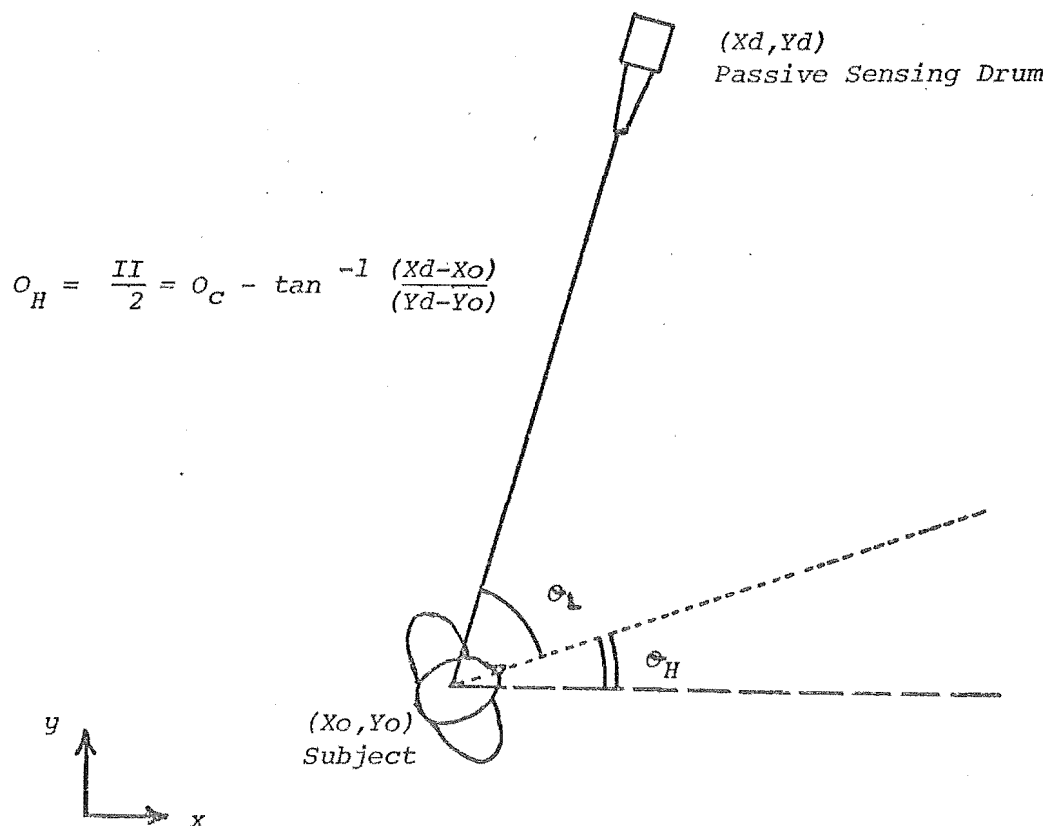


Fig. 5.4
Calculation of Head Orientation

x-axis is given by:

$$\theta_H = \frac{\pi}{2} - \theta_L - \tan^{-1} \left(\frac{x_d - x_o}{y_d - y_o} \right) \dots\dots\dots (5.1)$$

If it should be desired to simulate body-mounted devices (such as the Russell Pathsounder), body orientation relative to the head could be measured by a further potentiometer, and the result added to the head potentiometer measurement. Alternatively, body orientation could be measured directly by attaching the sensing linkage to a shoulder-mounted harness.

5.5:3 Obstacle Search Strategies

It was decided to commence by basing the simulation around a generalized version of the Single Object Sensor - thus eliminating the need to display more than one obstacle at once. In this case, the digital computer is required to perform the following operations in each sampling interval :

- (a) Compute position and head orientation of subject;
- (b) Decide which of the obstacles present in the room are within the beam of the simulated device;
- (c) Calculate range and direction of the closest of these obstacles;
- (d) Send signal generation command to the analog computer.

Items (a) and (d) between them require approximately 30 milliseconds, depending on the complexity of the functions used to calculate frequencies and amplitudes. Items (b) and (c), which may be grouped under the title of obstacle search routines, proved to be the most difficult portion of the software to produce in such a form that computation time limitations were satisfied.

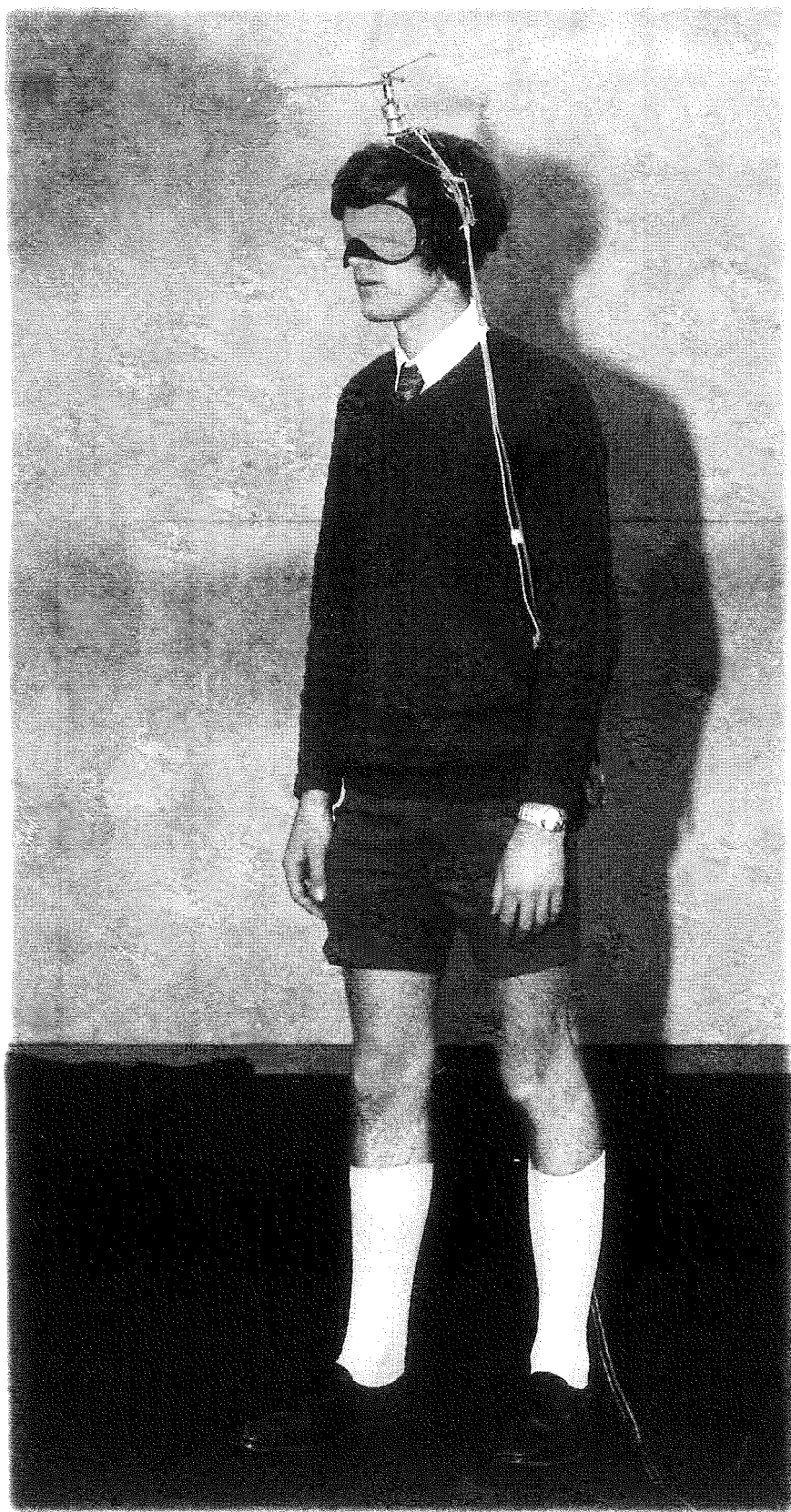


PLATE 3.

Simulation System Headgear.

An appreciation of the time-consuming nature of these search routines can be gained from Figure 5.5.

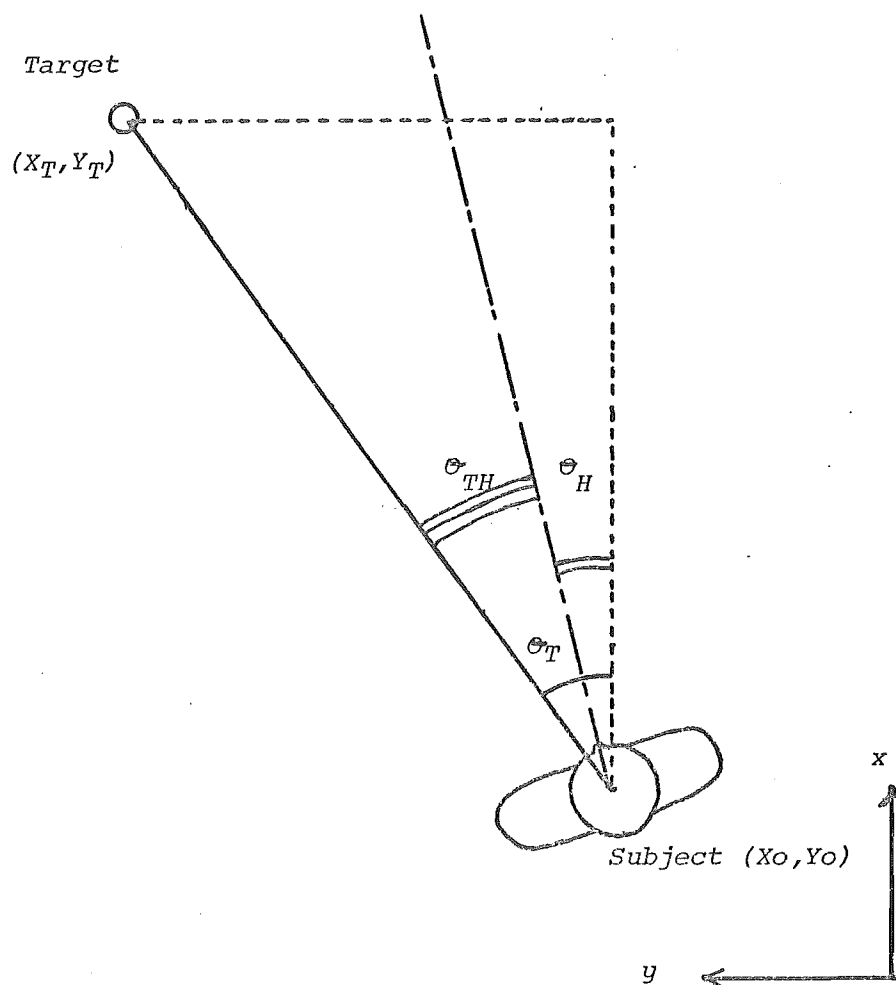


Fig. 5.5

Computation of Target Range and Azimuth

If θ_H is head orientation relative to the x-axis, θ_T is the angle subtended at the subject by a target and the x-axis, (x_T, y_T) is the

target position, and (x_o, y_o) is the subject's position, the azimuth of the target relative to the subject's head is

$$\theta_{TH} = \theta_T - \theta_H \dots\dots\dots (5.2)$$

$$\text{where } \theta_T = \tan^{-1} \left(\frac{y_T - y_o}{x_T - x_o} \right) \dots\dots\dots (5.3)$$

and the target's range is given by

$$R = \sqrt{(y_T - y_o)^2 + (x_T - x_o)^2} \dots\dots\dots (5.4)$$

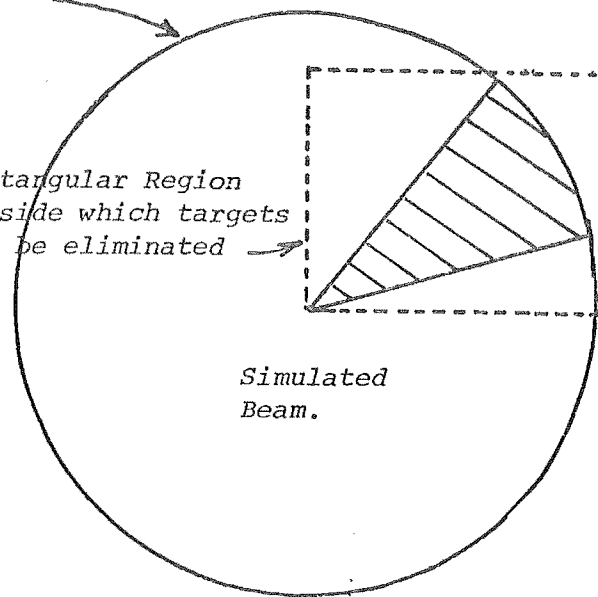
Unfortunately, each trigonometrical operation occupies 5 ms, as does a floating-point square root. Finding the ranges and azimuths of all targets present in the room and eliminating those outside the simulated device "beam" could therefore become a lengthy process.

To overcome this problem a preliminary search is used which eliminates all possible targets falling outside a rectangular region near the subject. In specifying this region, sine and cosine functions are approximated by quadratics to save computing time. Figure 5.6 illustrates the degree to which this preliminary search eliminates unwanted targets before ranges and azimuths of remaining objects are computed.

The search routines were tested in an arbitrary field of obstacles (Figure 5.7) with device beamwidth specified as 60° and range 4 m. For all values of head orientation, total searching time was less than 70 ms, allowing the 100 ms total sample time criterion to be easily met. In most situations the actual sampling time is somewhat less, as obstacles are seldom packed as closely together as those used in the test program.

Circular Region -- eliminating all objects
outside maximum
range

Rectangular Region
outside which targets
can be eliminated



Simulated
Beam.

Fig. 5.6

Search Strategy - Initial Elimination of Unwanted Targets

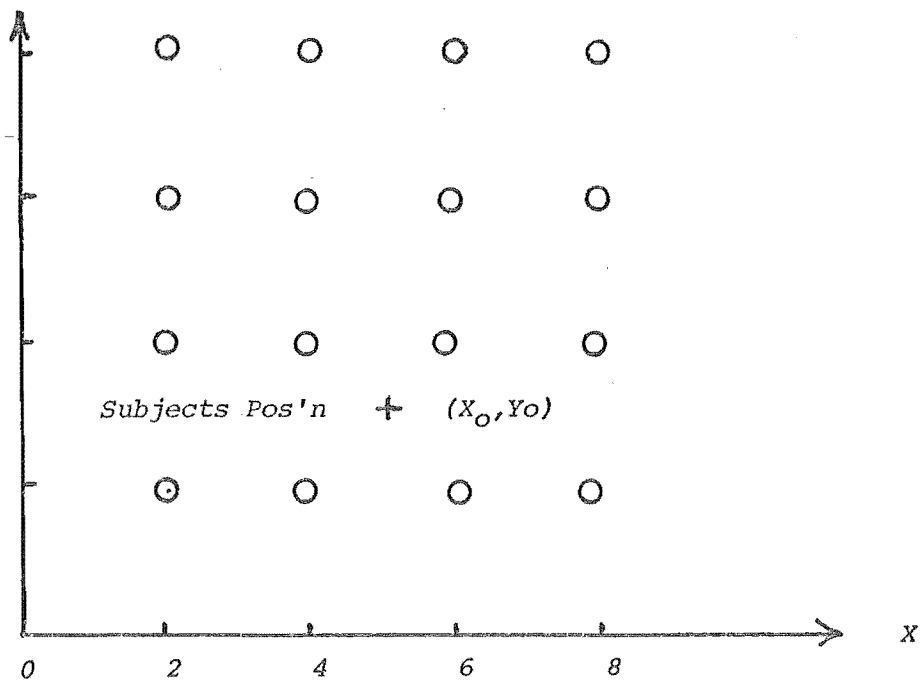


Fig. 5.7

Test Field of Obstacles

The final stage of the obstacle search routine is conceived in such a manner that extension to two or more targets being presented simultaneously in the display is a very minor matter, since all obstacles within the simulated device beam, together with their ranges, are known by the end of the search process.

5.5:4 Analog Computation.

The principal requirements for the analog side of the system were the monitoring of head position (section 5.5:2) and the production of an audio signal for each target present in the display. The patching diagram of Figure 5.8 illustrates the arrangement used in the system as built, for presentation of one target at a time. The Digital-to-Analog Multipliers (D.A.M.s) are directly addressable from the digital computer, and 3 are needed for each target - 1 for frequency control and 2 for independent amplitude control to each auditory channel. The low-pass filters on the outputs of the D.A.M.s are intended to smooth out the discontinuities caused by the discrete sampling nature of the system, and perform this function satisfactorily. Handset potentiometers provide manual channel balancing facilities should these be required.

Extension of the system to 2-target simulations merely requires the addition of 2 multipliers and 3 low-pass filters connected to the unused D.A.M.s 1, 3, and 5. Extension beyond 2 targets could be realized using the Binary Data Interface (B.D.I.) with suitable D-A converters.

The auditory signal is presented to the subject via headphones fed by a light cable, which also carries the head orientation potentiometer signal. A clip attaching this cable to the subject's belt ensures that the subject is virtually unconscious of any drag.

Frequency
Control
To V.C.O.

From V.C.O.

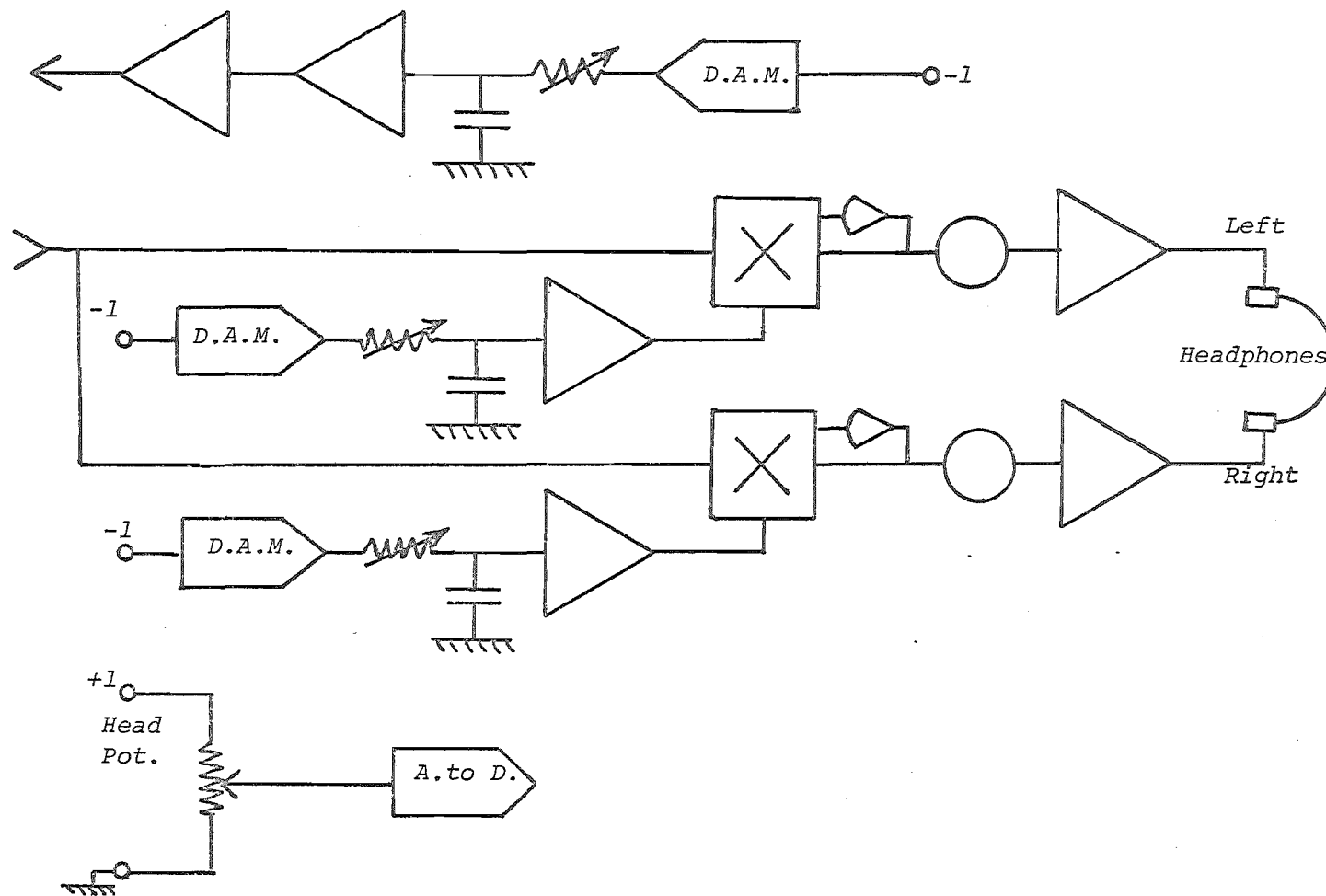


Fig. 5.8
Analog Patching Diagram

The system could easily be adapted to I.T.D. generation by using the D.A.M.s to drive voltage-controlled monostables (Figure 5.9) available in integrated circuit form. If only one object at a time was to be displayed, both I.A.D. and I.T.D. could be controlled simultaneously.

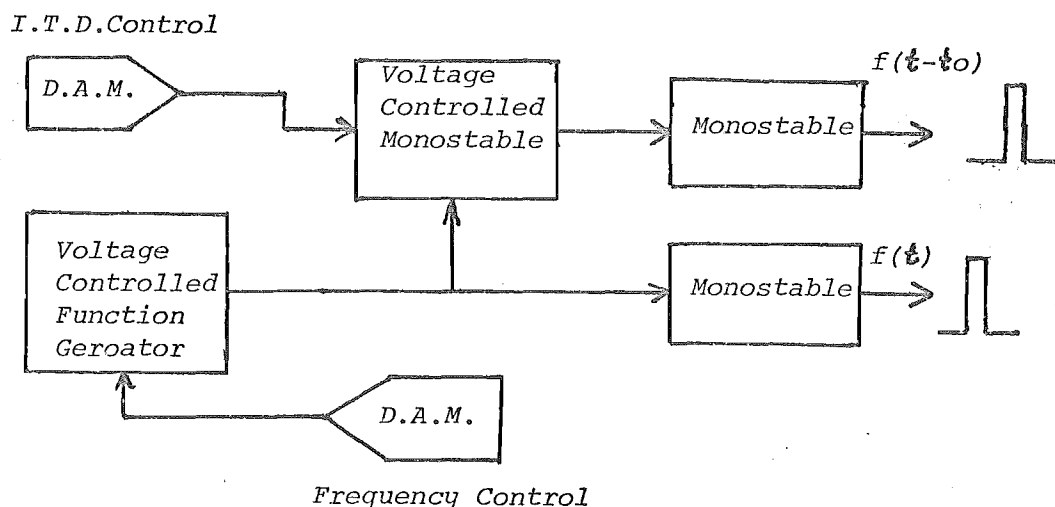


Fig. 5.9
Generation of I.T.D.

5.5:5 General Software Considerations

In considering signal generation software, it was desirable that as wide a range of simulated device cues as possible could be produced by on-line interaction with the operator. Consequently,

means were devised whereby maximum range, range coding, beamwidth, I.A.D., and beamshape can be varied at will by typed commands. In order to achieve this level of flexibility, it was necessary to formulate the polar response characteristics of the simulated device beam (Appendix 2) to allow independent variation of beamwidth, I.A.D., and loudness roll-off characteristics. Each of these parameters can be specified by typed commands to any desired numerical value. In addition, selection of linear or inversely-proportional frequency-range characteristic is possible by depressing or releasing an appropriate sense switch, while the constant of proportionality is specified using the teletype.

If it is desired to simulate device characteristics outside the range allowed by this system, a special purpose signal generation subroutine is written and used. For example, such devices as the Russell Path Sounder (10) and the Nottingham Obstacle Detector (11) can be simulated in this manner. A typical such special-purpose subroutine allows a choice between several numbered options selected by typing of the appropriate integer.

At any time between trials the user may transfer control to an option-specification mode by depressing a sense switch. In this mode, the program asks the operator which options it is desired to change, and the operator responds with yes/no commands or numerical values where these must be specified. In this manner, ideal paths (if any) are specified, together with such variables as obstacle positions, display scale and origin, and simulated device characteristics.

During experimental trials, although position is sampled and the display updated at least every 100 msec, position is stored only

at every second sample, conforming approximately to the sampling rate used in the normal monitoring system of chapter 3. The exact sampling rate varies according to the complexity of the environment and simulated display characteristics, and is normally somewhat in excess of the nominal 10 Hz figure. This has its effect on the RMSDAS, AVAC, and SCURV performance measures which, as explained previously (section 4.6:7), are sampling rate dependent, so that direct comparisons of these parameters with values obtained using the normal monitoring system must be viewed with caution. However the principal measures of path deviation (RMSDSL and RMSDIP) are unaffected.

To reduce the wasted time between trials to a minimum, only a limited selection of the performance indices (namely AVSP, AVAC, RMSDAS, RMSDIP, RMSDSL, SCURV) is printed out by the system, while the distance-versus-time graphs are suppressed. The option of punching the data out on paper tape for subsequent analysis is retained.

Storage limitations allow a maximum elapsed time of approximately 35 seconds for each trial. In practice, this has been found to be adequate. Typical trial times are of the order of 10-15 seconds. A multiphase version of the program was written and tested to provide opportunity for longer trial times, greater flexibility and performance analysis, and a wider choice of device displays without the need for subroutine changes. This was rejected because of the time wasted by phase-changes in on-line experimentation, but if future research required more sophisticated data processing or trial times longer than 45 seconds, a multiphase program would definitely be needed, unless core storage became available.

5.6 SIMULATION SYSTEM ERROR ANALYSIS.

5.6:1 Effects of Errors on Apparent Pole Positions

Consider the co-ordinate system of Figure 5.10, which depicts a subject travelling in the x-direction with velocity V and rotating his head at an angular velocity w . Let the average time delay caused by the insertion of the simulation system between real and perceived events be t_D , and let the errors in measurement of the subject's position in the x and y directions be E_x and E_y respectively. Further, let (x_p, y_p) be the real co-ordinates of a pole within the simulated beam, and (x_a, y_a) be its apparent position as presented to the subject via the auditory display. The following relations then hold, to a first order approximation:

$$x_a = x_p + Vt_D \pm E_x \quad \dots\dots\dots (5.1)$$

$$y_a = y_p + wrt_D \pm E_y \quad \dots\dots\dots (5.2)$$

where $r = \sqrt{x_p^2 + y_p^2}$

Consequently, the errors in the x and y co-ordinates of the perceived pole positions are, respectively:

$$\delta x = Vt_D \pm E_x \quad \dots\dots\dots (5.3)$$

$$\delta y = wrt_D \pm E_y \quad \dots\dots\dots (5.4)$$

While the maximum value of E_x would be approximately 2.7 cm (see section 4.3), the value of E_y will be greater than this because of the error, δ , in static head position measurement. This error is estimated to be less than one degree, resulting in an increment to E_y of $r\delta$, or approximately 3.3 cm maximum. This would give a peak value (seldom attained) for E_y of approximately 6 cm.

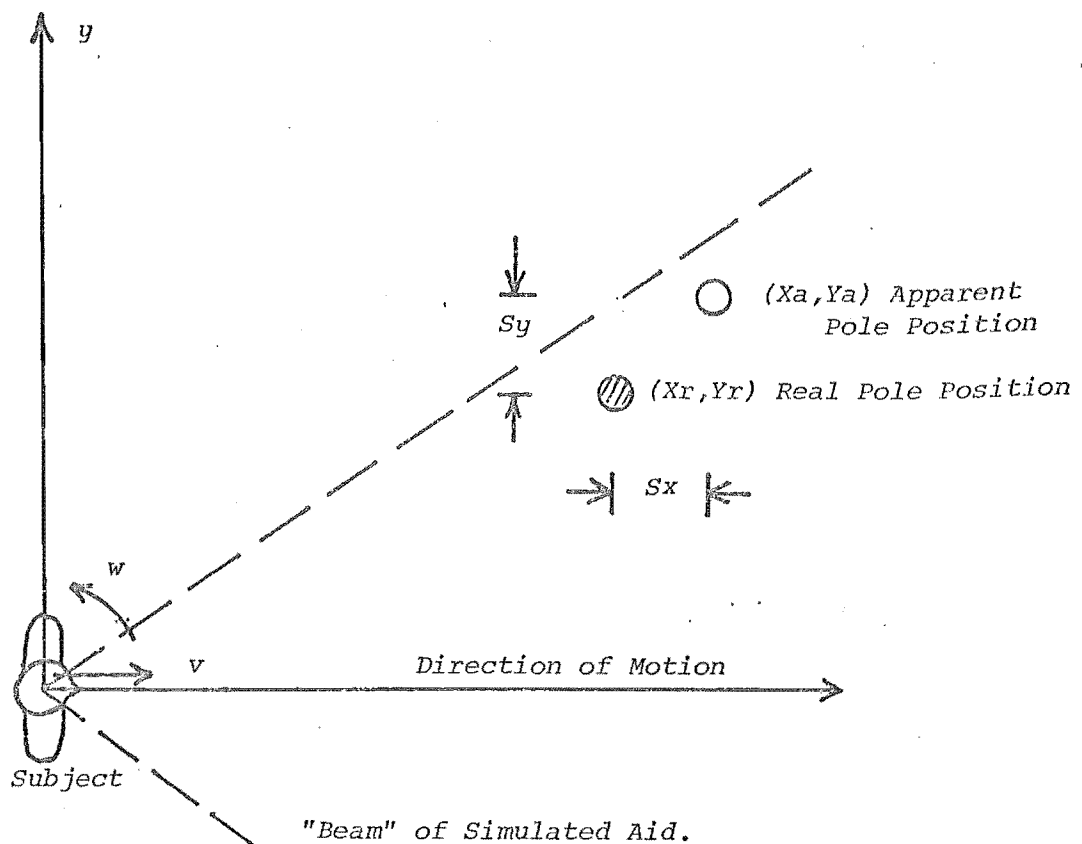


Fig. 5.10

Co-ordinate System for Error Analysis

Typical values of V_t are approximately 8-12 cm, while w could be up to 20 cm for $w = 1$ rad/sec and $r = 2$ m, representing a peak dynamic azimuth error of approximately 6° .

5.6:2 Effects of Errors in Apparent Pole Positions on Subject Performance

The ability of the human subject to estimate the true positions of objects given the above errors is unknown. For example, head rotation if it occurs at all is likely to be oscillatory, introducing errors in the y co-ordinate which average to zero over time, thus facilitating estimation of the true azimuth of an object.

Leaving aside these unfathomables, an estimate may be obtained for the likely limit of attainable performance in terms of the RMS path deviation indices used in measurement. Good performance involves

very little head rotation - too much movement of the head being unnatural in terms of normal sighted travel. Considering the errors involved in a shorelining or pole-apparent type task, an estimate of δy for the best possible case is simply $\pm E_y$ (from equn 4 when $w = 0$).

In estimating δx , the error term Vt_D in equn 5.3 merely shifts the whole shoreline along its own axis by a constant amount throughout the execution of the task (assuming speed is approximately constant and the subject's path does not undergo violent fluctuations), while the $\pm E_x$ term shifts each element of the shoreline forwards or backwards by a small amount.

The likely range of errors in the position of a shoreline pole is illustrated in Figure 5.11.

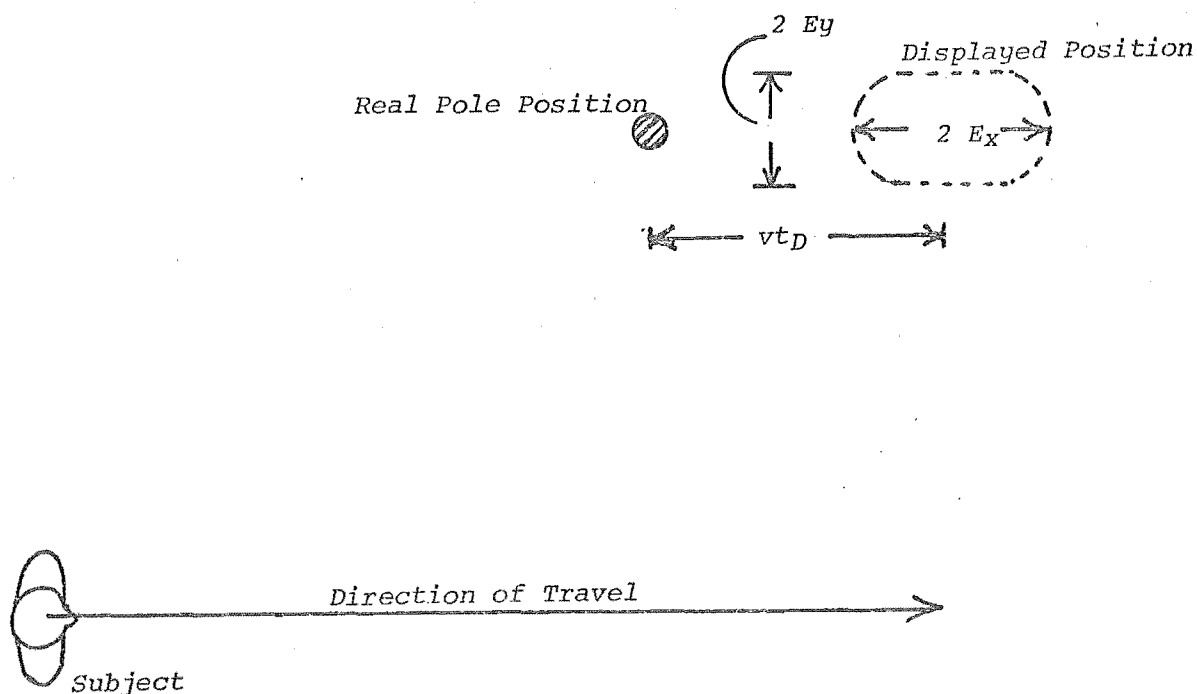


Fig. 5.11

Possible Errors in Displayed Pole Position

In determining the effects of these errors in performance, it should be noted that any movement of the shoreline to and fro along its own axis does not in principle set an upper bound to shorelining accuracy (in terms of path deviations), whether or not the apparent x co-ordinate of the poles is correctly interpreted (Figure 5.12).

The errors in the y co-ordinate, on the other hand, can place a direct limit on performance of the task. Attempts to follow accurately a shoreline which appears to move from side to side (Figure 5.12) would, with a suitable display which allowed perception of these movements, ideally result in similar oscillations of peak magnitude y in the subject's path. Since $\pm E_y$ is a maximum value for this error under the conditions described, it might be expected that r.m.s. values of path deviations would limit at approximately $\frac{E_y}{\sqrt{2}}$ or 4 cm.

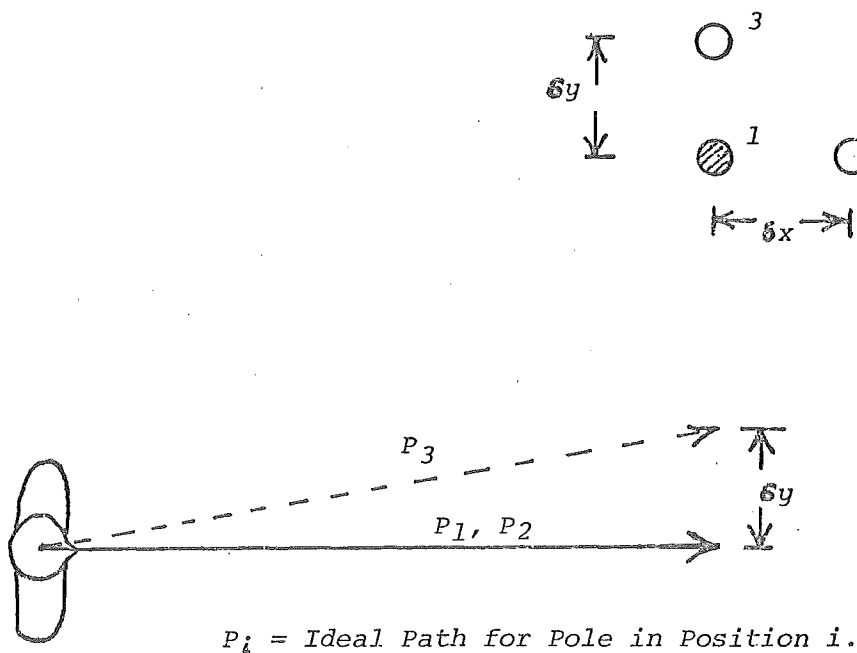


Fig. 5.12

Effects on Ideal Path of Shifts in Apparent Pole Positions

This value is greater than the minimum values of RMSDSL achieved in practice with experienced subjects using devices with exaggerated cues (section 6.5 below). This illustrates the conservative nature of the above calculations and the degree to which human subjects can smooth out the effects of noise in the display. Observed values of RMSDIP, however, have not yet reached this level, suggesting that the system errors described above are not the limiting factors in minimising this performance index. A more likely constraint in this case is the inherent difficulty of making absolute distance judgements with most types of display. Minimising RMSDSL requires only relative judgements as no ideal distance from the shoreline is specified (section 4.6).

5.7 SYSTEM EVALUATION.

5.7:1 Simulation of Single Object Sensor

The first device to be simulated was the Single Object Sensor, under development at Canterbury, whose simple display is described in section 5.3. The auditory signals produced by this device are 1 ms pulses with a repetition rate (PRF) described by :

$$\text{PRF} = \frac{177}{R} \dots\dots\dots (5.5)$$

where R is the range of the target in metres. This characteristic was simulated using the voltage-controlled function generator (Figure 5.8) set to produce pulses of very low mark-space ratio - indistinguishable to the ear from 1 msec "clicks". Several persons were given the opportunity of testing the simulated display using various environmental arrangements. Although it is hard to justify claims of realism, the subjective impression of the subjects was that the simulated display was difficult to distinguish from the real one

except in producing a clearer and more reliable signal in multiple target situations than the actual device, which was then suffering from teething troubles.

At the time, modifications to the Single Object Sensor to produce different output waveforms were under consideration, as the clocks were considered unpleasant by many. The simulation system was used to assist in this investigation. Differing waveforms could be selected using the options available on the function generator.

A simulated version of the Single Object Sensor was later used (see chapter 7) to investigate effects on user performance of externalization of display sounds.

5.7:2 "Sonic Glasses" Simulation Problem

Although it was not intended to attempt an exact simulation of such a complex display as that of the Binaural Sensory Aid or "Sonic Glasses", it was found that subject to certain restrictions, useful information could be obtained by simulating a somewhat abstract version of the device.

A brief description of the Sonic Glasses was given in chapter 3, and further details appear below.

The cues presented to the user by this device are many, and as yet their utilisation by blind pedestrians moving through complex environments is incompletely understood. Briefly, an object situated within the beam of the sonar gives rise to a binaural signal of a frequency proportional (850 Hz/m) to the range of the object. This signal approximates a pure tone - continuous except for the blanking periods inherent in the display - for a range of simple

targets such as shop windows, the surrounds of doorways, poles, and parking meters. A more complex target, such as a bush, gives rise to a complex of tones covering a band of frequencies centred on the pitch corresponding to the object's range. Two main cues to direction are generated by the device as presently supplied commercially. The interaural amplitude difference (IAD) of the binaural signal is proportional ($0.3 - 0.5$ dB/degree) to the azimuth of a target, resulting in an explicit left-right cue (Figure 5.13a). This effect relies on the polar responses of two splayed receiving transducers (Appendix 2). An additional direction cue is generated by the overall loudness fall-off of the binaural signal as a target moves away from the centre of the field of view towards either side (Figure 5.13b).

This fall-off amounts to at least 20 dB in each channel in the commercial device, between the beam centre and points at 45° to either extreme, and up to 45-50 dB to 90° in the periphery. Although initially this cue might appear to be ambiguous, it ceases to be so when head movement of the device wearer is allowed for. Considering a monaural device with only this loudness cue to direction, it is evident (Figure 5.13b) that if the subject rotates his head to the right and the signal loudness increases, then the target must be located in the right-hand half of the beam.

The Sonicguide is capable of displaying more than one object at a time, though confusion arises when both are at similar ranges. Further complexity is introduced by the effect of Doppler shift on the range cue - an effect, however, which at normal walking speeds is important only at very close ranges (less than 1 m). It is of minor

importance at the longer ranges generally encountered in mobility situations and is, in any case, more of an artefact than a designed-in cue.

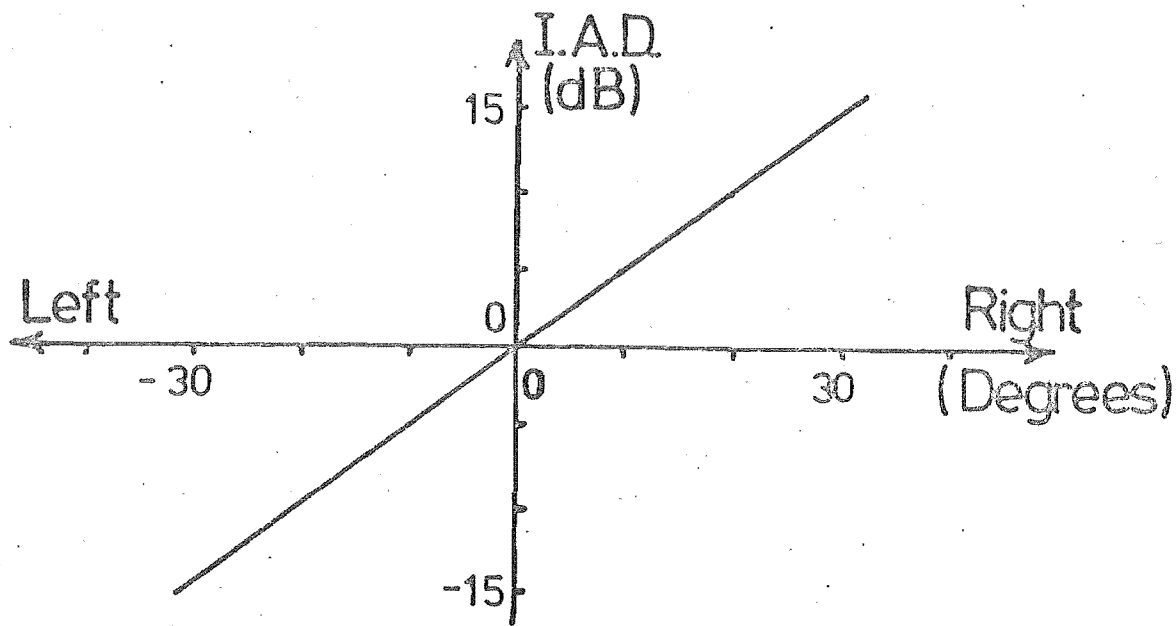
In simulating the basic cues of the Sonicguide the Doppler effect was ignored, and a continuous signal with no blanking pauses (inclusion of which would add nothing in terms of information) was used. To ease the task of simulation and avoid adding unnecessary confusion to the basic issues at stake, all objects were assumed to be of the simple type (such as poles) mentioned earlier, and only one object at a time - the closest if more than one were present within the sonar beam - was presented to the display. Beamwidth (defined at the 30 dB roll-off points) was set at 60° .

The main, salient features of the Sonicguide - the range cue and the two direction cues - I.A.D. and overall loudness contour - were simulated and all made independently variable. These were the basic features deliberately designed into the Binaural Sensor, and were of the most interest from the points of view of both display information content and actual design improvement.

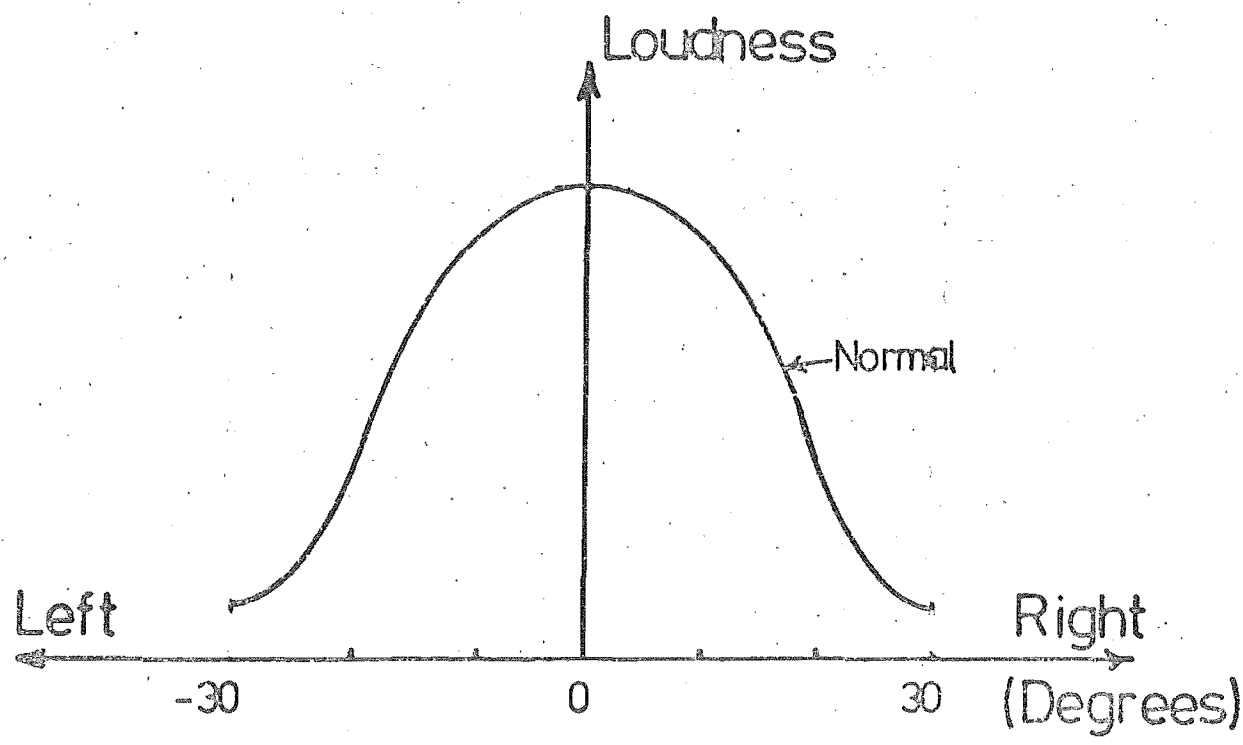
5.7:3 Validation of "Sonic Glasses" Simulation

The type of simulation described above was thought to be of value in investigating the effects of varying basic device cue parameters of the type present in the "Sonicguide". Results of such studies are reported in Chapter 6, but outlined below is a demonstration of the basic relevance and validity of the simulation, and the ease with which an experienced user of the Sonicguide was able to transfer to the simulated device with no loss in locomotor control performance.

The shortage of experienced, skilled Sonicguide users within



(a)



(b)

Fig. 5.13
Idealized Direction Cues

reach of the mobility laboratory is severe, but one such subject offered his services for this study. He had been an active Sonicguide user for seven years, being in fact the first person to be trained in 1969, and had travelled independently both within New Zealand and around the world using the device. His pattern of use consisted of wearing the Sonicguide for his frequent trips into the city and further abroad, while often preferring to rely merely on a long cane for travel in his more immediate, familiar suburban environment. Although his formal mobility training had been negligible, he was generally agreed to be a most skilled blind traveller.

It was desirable to choose a task for which a good deal of data had previously been gathered from subjects acting under various conditions of sensory input including normal vision. The main task used here as a basis for comparison was that of shorelining a row of poles at a constant distance. This task is representative of the real world mobility situation, and in terms of the signals produced by the Sonicguide is akin to walking parallel to a row of shop windows.

The geometrical layout is illustrated in Figure 5.14. Six poles forming the "shoreline" were positioned in a straight row with 2 metre spacings. A seventh pole, 1 metre away from the shoreline, was used as a starting position. As each trial commenced, the subject faced the starting pole and was asked to turn through 180° , orient himself using the display signals, and walk down the shoreline remaining as nearly parallel to it as possible.

The subject was first tested using his own Sonicguide. Numerical performance indices (Table 5.1) were averaged over 10 recorded

trials after the subject had completed 6 practice trials.

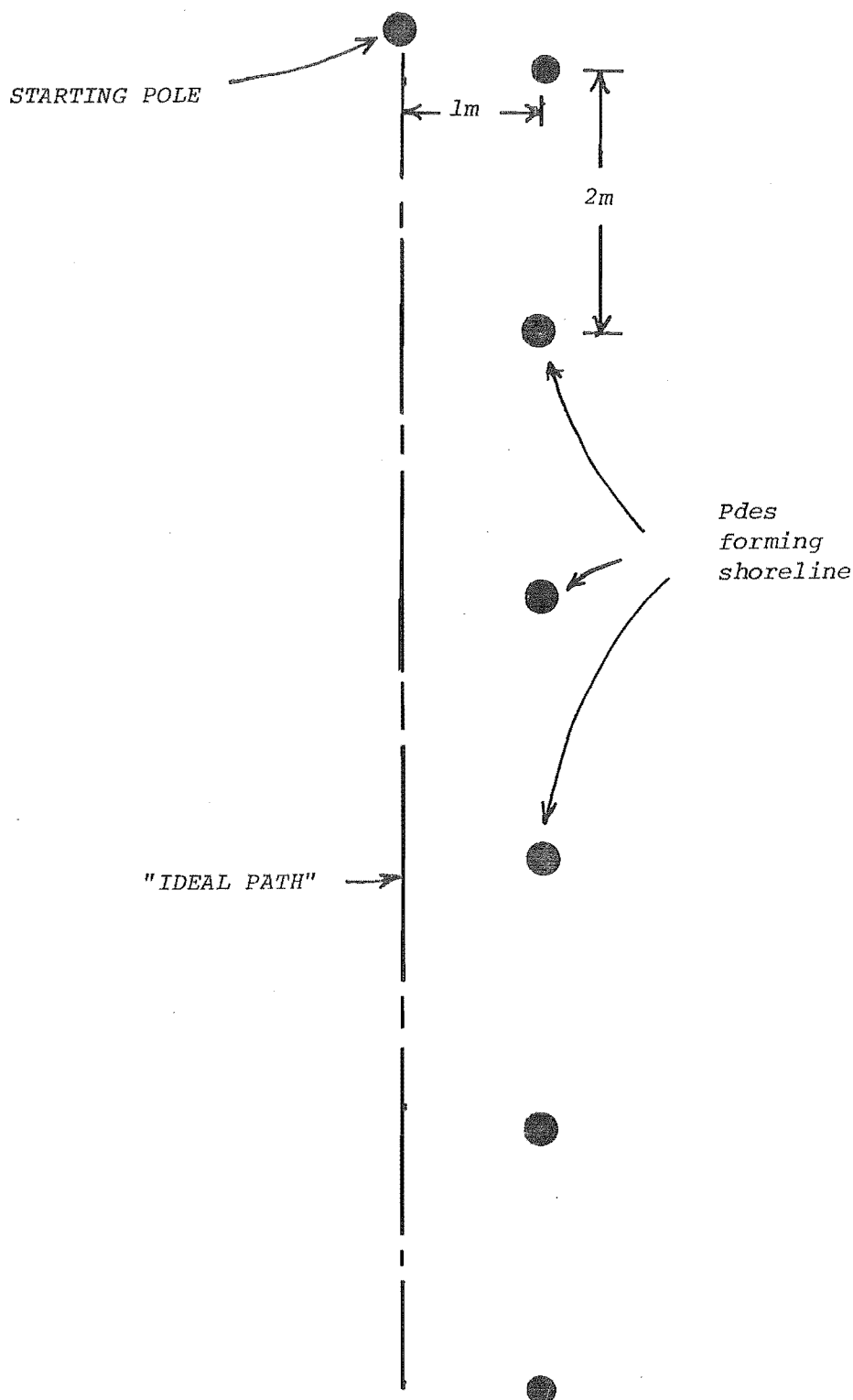


Fig. 5.14
Shoreline Task

A typical path plot for this condition appears in Figure 5.15,

together with a typical plot from a normally sighted subject. The apparently poorer path straightness evidenced by the Sonicguide user is born out in the numerical indices of Table 5.1, in which the values for sighted performance represent an average over 6 subjects each performing the task 6 times.

It is evident that, overall, average speed (AVSP) was higher for the Sonicguide user than for the sighted subjects. This and other aspects of the subject's behaviour while using the normal Sonicguide are discussed elsewhere, but it suffices to recall here that AVSP is not regarded as being of major importance as a performance index as long as its value lies somewhere in the range from, say, 80 to 160 cm/sec, representing the limits of an acceptable, normal walking pace.

TABLE 5.1

<div> <div>Condition</div> <div>Performance Index</div> </div>	Sighted	Sonicguide	Simulated Display (No practice)
AVSP (cm/sec)	120	143.7	127.3
RMSDIP (cm)	7.6	16.8	18.7
RMSDSL (cm)	3.2	7.7	6.5

AVSP = Average Speed

RMSDIP = RMS Deviation from Ideal Path

RMSDSL = RMS Deviation from Straight Line

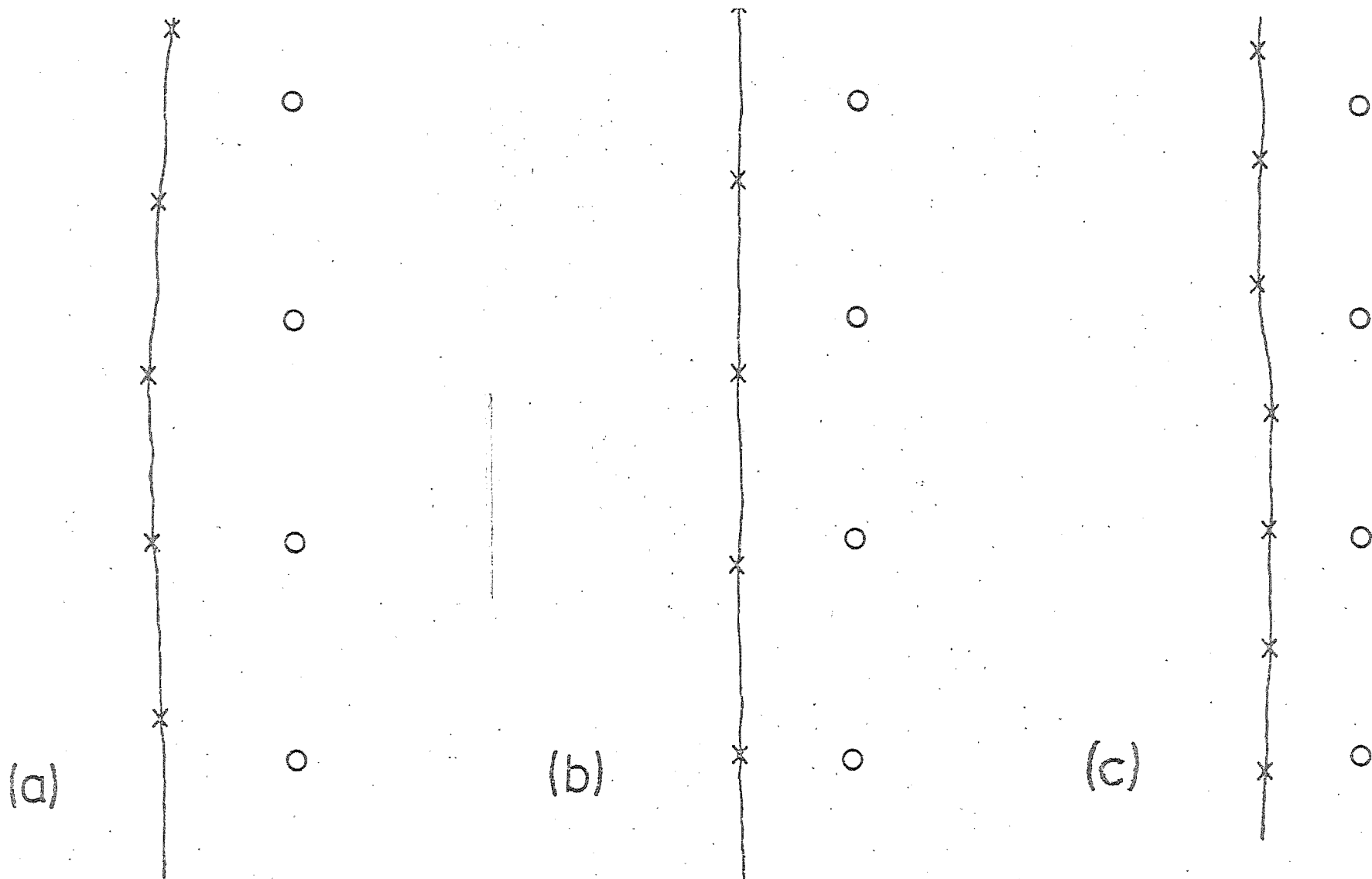


Fig. 5.15

Shoreline Paths : (a) Sonicguide; (b) Sighted; (c) Simulated Device

RMSDSL is probably the fairest and most useful index of performance applied to the shorelining task (see section 4.8). It is apparent from Table 5.1 that both RMSDIP and RMSDSL were greater for the Sonic guide user than for the sighted subjects, indicating a loss of control due to the poorer quality of sensory information provided by the artificial aid.

After completion of the trials using the normal Sonicguide, the subject was given the simulated version of the device and asked to repeat the shorelining task. No practice was allowed. Ten trials were recorded, and the path from a typical trial (Figure 5.15c) indicated comparable performance to that obtained using the real Sonicguide. Numerical results from these trials appear in Table 5.1. Average speed (AVSP) for this and all succeeding conditions was well within the normal range of acceptable performance. Of greater interest are the RMSDIP and especially the RMSDSL values. The latter was seen to be marginally lower for the simulated condition than the real Sonicguide condition, indicating a slight improvement in performance. However, this difference was not statistically significant. What was perhaps surprising was that the subject remarked upon the ease with which he could transfer from the real to the simulated system. The essential realism of the simulation was confirmed both by his remarks and by the fact that without any practice he could achieve levels of performance comparable with his Sonicguide performance.

Further confirmation of the simulation system's basic validity was obtained when testing a 7-year old blind child who had been trained to use a special version of the Binaural Sensor with a range code of 1.5 kHz/m, and a beamwidth of 75° . Similar procedure

to the above was adopted, with the variation that 1 metre pole spacing was used. Results for the shorelining task using real and simulated versions of the aid appear in Table 5.2, in which performance is averaged over two sets of 6 trials in each condition (recorded on different days and in different orders to reduce order effects). Performance is seen to be similar in both conditions.

TABLE 5.2

*Performance Using Real & Simulated Child's Aids
(Means over 12 trials)*

<i>Condition Index</i>	<i>Real Aid</i>	<i>Simulated Aid</i>
<i>AVSP (cm/s)</i>	<i>41.6</i>	<i>52.3</i>
<i>RMSDSL (cm)</i>	<i>9.5</i>	<i>8.5</i>
<i>RMSDIP (cm)</i>	<i>33.0</i>	<i>45.5</i>

5.7:4 Discussion

It may be argued that the fact that similar performance was obtained by subjects using real and simulated devices merely reflects the measuring system's inability to discriminate adequately. It is very difficult to prove a null hypothesis, but in this case other evidence assisted in drawing a conclusion.

When the simulated cues were changed so that they differed from the normal value, significant changes in performance were noted (see chapter 6). Furthermore, when the cues were returned to their normal values as a control condition, performance similarly reverted

to the original level. Hence it appeared that some reasonable degree of validity could be claimed for the simulation technique, at least under the controlled environmental conditions used in this type of study.

5.8 CONCLUSIONS.

A simulation system has been described which permits real-time mobility aid simulation using a real, controlled environment and mobile subjects. This system brings to realization a long-standing research goal in the field of blind mobility.

The performance measurement capability of the instrumentation system described previously has been retained, allowing objective measurement of the performance of controlled environment tasks by subjects using real or simulated aids.

The system is sufficiently flexible to allow simulation of a wide variety of relatively simple displays with little change to hardware or software, and allows subjective and/or objective assessment to be made of the effects of proposed changes to existing devices.

These features should prove useful in the development of future mobility aids.

REFERENCES

- (1) Mann, R.W.; "Mobility Aids for the Blind - an Argument for a Computer-Based Man-Device Environment, Interactive Simulation System". Proc. Conf. on Evaluation of Mobility Aids for the Blind. Nat. Academy of Engineering, Washington, D.C., 1971.
- (2) Dupress, J.K.; "Sensory Aids Evaluation : Procedures and Instrumentation:.. In R. Dufton (Ed.), Proc. Conf. on Sensory Devices for the Blind. London : St. Dunstan's, 1966.
- (3) Nye, P.W., Bliss, J.C.; "Sensory Aids for the Blind : A Challenging Problem with Lessons for the Future". Proc. IEEE, 1970, 58 , 12, 1878-1898.
- (4) Mann, R.W.; "Evaluation and Simulation of Mobility Aids for the Blind:.. AFB Research Bulletin, 1965, 11, 1-62.
- (5) Baecker, R.M.; "Computer Simulation of Mobility Aids: A Feasibility Study". AFB Research Bulletin, 1968, 16, 141-205.
- (6) Mills, A.W.; "Toward an Empirical Theory of Mobility". Research Note, Tufts University, Dept. of Psychology, Medford, Mass.
- (7) Mills, A.W.; "A Simulation Approach to the Development of Mobility Aids for the Blind". Proc. Conf. on Evaluation of Mobility Aids for the Blind. Nat. Academy of Engineering, Washington, D.C., 1971.
- (8) Kay, L. Bui, S.T., Brabyn, J.A., Strelow, E.R.; "Single Object Sensor : A simplified Binaural Mobility Aid". Journal of Visual Impairment and Blindness, May 1977, 210-213.
- (9) Kay, L.; "Auditory Perception and its Relation to Ultrasonic Blind Guidance Aids". J. Brit. Inst. Radio Engineers, 1962, 24:
- (10) Russell, L.; "Travel Path Sounder - Further Results". In R. Dufton (Ed.), Sensory Devices for the Blind, London, St. Dunstan's, 1966.
- (11) Armstrong, J.; "Summary Report of the Research Programme on Electronic Mobility Aids". Report, Psychology Dept, University of Nottingham, 1973.

CHAPTER 6

EFFECTS OF SIMULATED CUE VARIATIONS
ON USER PERFORMANCE6.1 INTRODUCTION.

Following speculation regarding the possible effects of varying the cues produced by the Sonic Torch (1), and later, the Sonic Glasses (2), the present chapter reports a series of experiments designed to investigate what effect, if any, variations of range and direction cues have upon the locomotor control performance of an aid user. This information could assist both in estimating the relative importance of different cues and in proposing improvements to existing devices.

The characteristics of the "simulated" aid described in chapter 5 fell somewhere between the Single Object Sensor (S.O.S.) and the Sonicguide. An exact simulation of either device allowing for Doppler Shifts, noise, etc. would have been impractical, and such an attempt would still have left open to question the extent to which any results obtained applied to the real aid. The solution therefore, was a compromise between the desire to simulate a real aid and the desire for results which could be generalized to a range of acoustic aids. The simulation eventually used in the present studies was therefore more of a hypothetical aid which, while closely resembling the Sonicguide, had many features of other aids such as the proposed S.O.S.

Following a number of informal pilot studies investigating cues such as :

- (a) $f \propto r$
- (b) $f \propto \frac{1}{r}$
- (c) $f \propto e^{kr}$
- (d) $f \propto e^{-kr}$

(where r represents target range and f represents frequency), it was decided to perform a formal set of experiments to investigate the separate effects of range and direction cue variations on the performance of the shorelining task. This task was chosen for its relevance to mobility, the fact that it allowed accurate measurements to be made, and the fact that some data on its execution under various conditions had already been collected. Device parameters were as described in chapter 5, with beam width set to 60° , and range to 3 m, while sinusoidal signals were used.

6.2 EFFECTS OF RANGE CUE VARIATION.

6.2:1 Experimental Conditions

To investigate the effect of variations in range cue, four conditions were selected for study. In each condition, a signal pitch rising with range was used, the constant of proportionality being successively increased from zero to 10, 100, and 1000 Hertz per metre. A difficulty quickly became apparent in attempting to design the "low range cue" part of the experiment, as a characteristic of, say 10 Hz/m would result in most signals being below the audible frequency threshold. This problem was overcome by adopting the scheme illustrated in Figure 6.1, so that no frequency below 100 Hz was encountered in the 0 and 10 Hz/m conditions. Thus the frequency range relationships for the chosen conditions were :

- | | | |
|-----|----------------------------|-----------------------|
| (a) | $f = 100 \text{ Hz}$ | (0 Hz/m) |
| (b) | $f = 100 + 10R \text{ Hz}$ | (10 Hz/m) |
| (c) | $f = 100R \text{ Hz}$ | (100 Hz/m) |
| (d) | $f = 1000R \text{ Hz}$ | (1000 Hz/m) |

where f is frequency in Hertz and R the range in metres.

The chosen values of frequency cue covered as wide a range of stimulus variation as would be feasible for a mobility aid with a pitch cue for range. No known aids use output frequencies above 5 kHz. In designing the experiment, it was postulated that the most important factor affecting user performance was likely to be the perceived rate of change of frequency with range, the direction of change ($f \propto r$ or $f \propto \frac{1}{r}$) being immaterial except insofar as secondary effects on direction cues were concerned. Investigation of these effects is left to future research.

6.2:2 Procedure

The shorelining task used in this study is described elsewhere (section 5.9). A between-subjects design was used for the experiment to eliminate transfer effects, and 6 subjects were tested in each condition. All subjects were normally-sighted and were excluded if they reported any hearing defects. If necessary, unbalance between the ears could be compensated for by adjustment of potentiometers 00 and 02 (Figure 5.5). The subjects were 3rd year electrical engineering students who were familiar with the general features of the Sonic Glasses through their course work and design projects.

Each subject performed 15 trials, of which the first 5 were regarded as practice, and included one trial in which he was guided

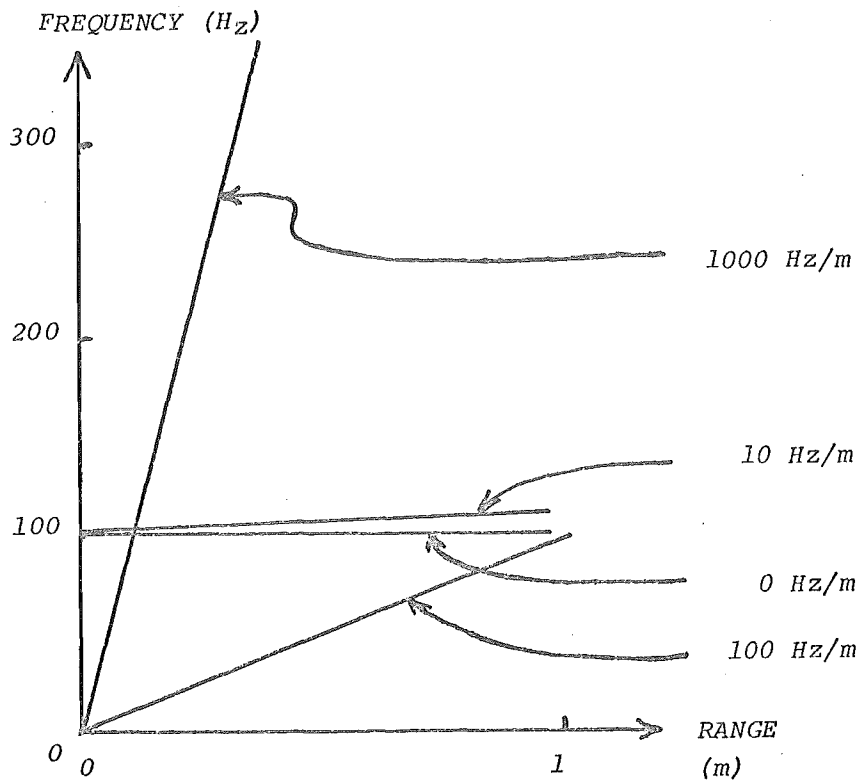


Fig 6.1
Simulated Range Cues.

TABLE 6.1

Variation of RMSDSL with Range Cue - (Summary over last 5 trials)

Hz/m	0	10	100	1000
RMSDSL	18.6	16.8	13.2	10.1

along the correct course by the experimenter. Results were summarised over the last 10 and the last 5 trials. The subject was permitted to remove his blindfold at the end of each trial in order to observe his final position.

As in the experiments described in chapters 4 and 5, before beginning each trial the subject was required to blindfold himself, facing 180° away from the correct path, and then orient himself for the trial using only the simulated device signals.

6.2:3 Results

Table 6.1 lists averages of RMSDSL over the last 5 trials.

In Figure 6.2., averages over the last 10 trials of RMSDSL, RMSDIP, AVSP, "Jerkiness" (defined as RMSDSP divided by AVSP), and SCURV are plotted against range cue in Hz/m. All of these measures appeared to show a tendency towards better performance as the range cue was enhanced. Analyses of variance showed significant effects for RMSDSL ($F(3,16) = 3.38, P < .05$) over the last 5 trials, and for AVSP ($F(3,16) = 4.35, P < .05$), and SCURV ($F(3,16) = 4.36, P < .05$) over the last 10 trials.

As the range cue was enhanced, average speed rose, indicating a rise in confidence, while path deviations (RMSDIP, RMSDSL, SCURV) fell, indicating superior locomotor control.

The results indicated that changes in the range code definitely affect performance, although relatively large variations are needed (e.g. 1000 - 100 Hz/m) before significant differences result. This suggests that little improvement could be effected in the present Sonicguide performance by variation of the range cue,

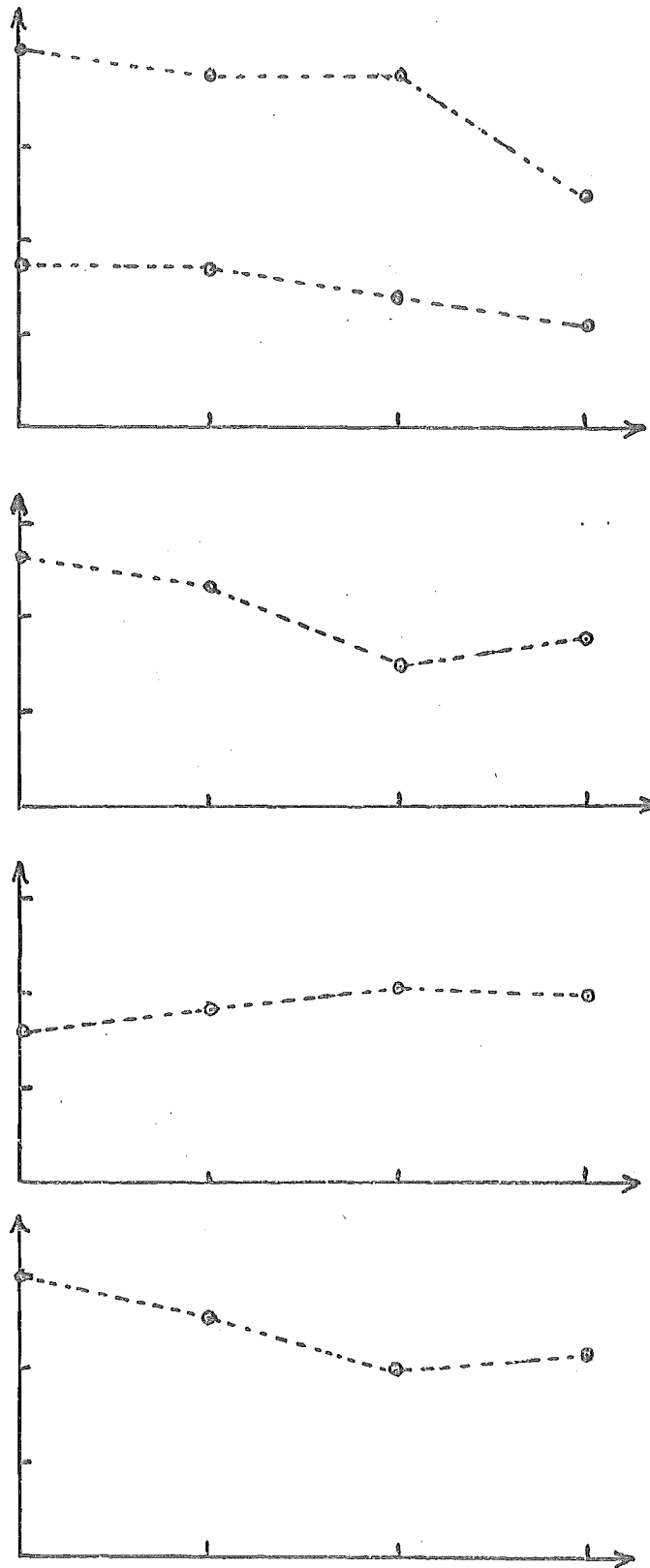


Fig. 6.2

Effects on Performance of Range Cue Variation

since scope does not exist for the large increase in frequency-range coding which would evidently be required. Present operation is at 850 Hz/m, and any large increase would result in either reduced maximum range or risk of exceeding the bandwidth of the auditory system - particularly in the case of older users who often possess high-frequency hearing loss.

6.3 EFFECTS OF DIRECTION CUE VARIATION.

6.3:1 Experimental Conditions

An experiment, complementary to the above, was performed to investigate the I.A.D. direction cue while the other parameters (section 6.2) were held constant. The range cue was set at 1000 Hz/m, while I.A.D. values of 0, 0.5, 1, and 2 dB/degree were tested. It should be recalled (see chapter 5) that even in the 0 dB/degree case, some remaining direction cue is provided by the fall-off in loudness as an object moves off to either side of the device's beam (Figure 5.13). Under dynamic conditions, this loudness cue is unambiguous, as explained in section 5.7:2.

6.3:2 Experimental Procedure

A between-subjects design was again used, but the 3rd year engineering students were unavailable for this experiment and the subjects used were students, technicians, and non-university personnel from a variety of backgrounds. More difficulty was experienced in training than in the previous experiment, and it was decided to develop a revised and systematic approach to the training problem. The 10-trial training program listed in Appendix 1 was developed and used.

As in the previous experiment, training was preceded by a verbal explanation of the basic concept of the simulated display and its cues to distance and direction. The subject was then blindfolded for the remainder of the experiment. During the 10 recorded trials succeeding the training program, feedback was given only if asked for. At the end of each trial the subject was led back to the starting point by the experimenter. Orientation at the beginning of each trial was as for the previous experiment, using only the simulated device signals.

6.3:3 Results

Table 6.2 and Figure 6.3 illustrate the variation of RMSDSL with IAD, while the results of an analysis of variance appended to the table, showed that significant effects ($P < .05$) were present.

TABLE 6.2

Variation of Performance with I.A.D.

<i>I.A.D. (dB/deg)</i>	<i>0</i>	<i>.5</i>	<i>1</i>	<i>2</i>
<i>RMSDSL (cm)</i>	16.7	17.5	15.2	10.9

Analysis of Variance:

	<i>DF</i>	<i>MS</i>	<i>F</i>	<i>P</i>
<i>Cond.</i>	3	52.07	3.25	$P < .05$
<i>Between</i>	20	16.02		

Introduction of small amounts of inter-aural amplitude differences had little or no beneficial effect, and may have served only to confuse the subjects. Further increases, however, significantly improved performance, suggesting that the present Sonicguide specifications of 0.3 - 0.5 dB/degree may not be optimal.

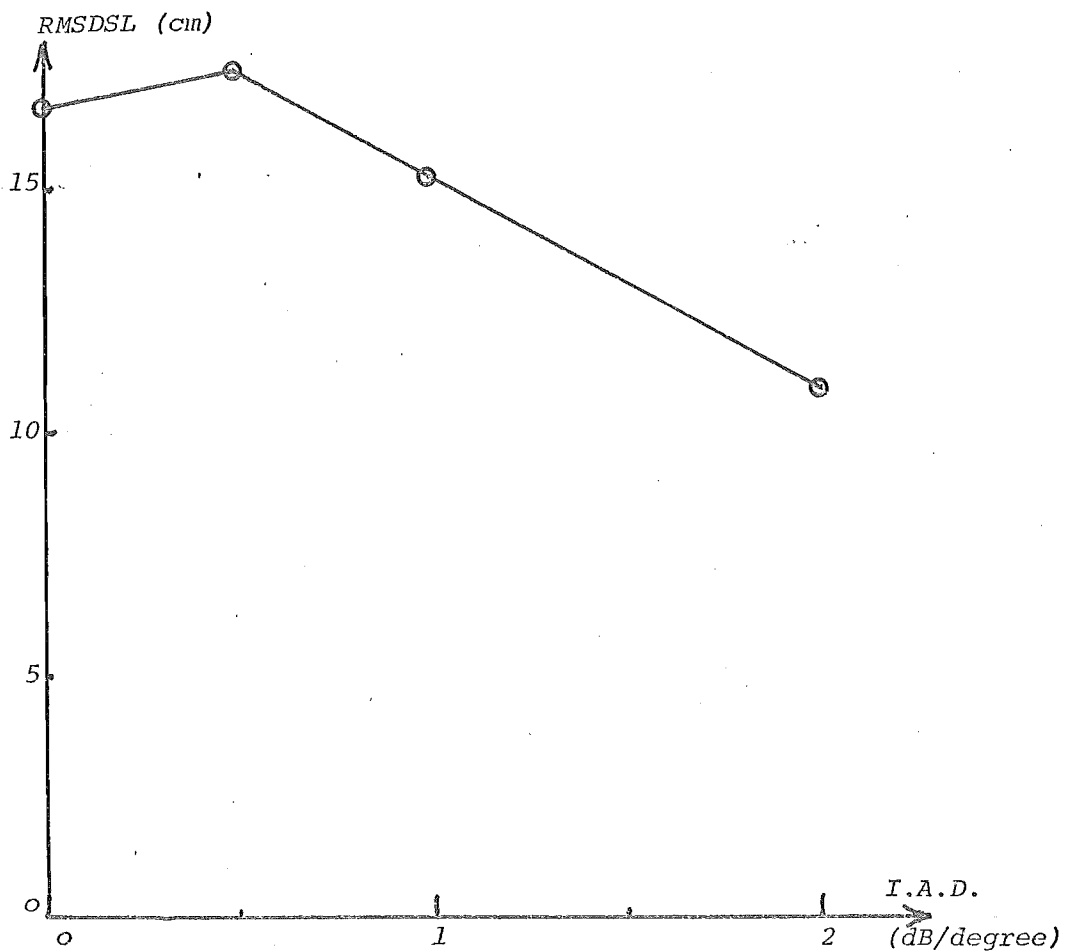


Fig. 6.3

Dependence of Performance on Direction Cue

The level of performance in the "normal" (1000 Hz/m, 0.5 dB/degree) condition was lower overall than that obtained in the earlier range cue experiment. This reflected the difference in back-

ground of the subjects used, and the change in training procedure. The subjects generally displayed less confidence than those used in the range cue study, and were less acquainted with the characteristics and capabilities of sensory aids such as the one simulated. Procedural differences such as a reduction in feedback during the recorded trials would also help to account for the observed difference.

6.4 SUPPLEMENTARY DATA FROM A LONG-TERM AID USER.

6.4:1 Introduction

The above experiments using naive, sighted (but blind-folded) subjects established trends in performance as cues were varied. However, because the exposure of each subject to a given simulated mobility aid was necessarily short, it was unlikely that an ultimate plateau of performance could be reached.

The complementary approach reported in the present section was to investigate the behaviour of an experienced aid user under simulated conditions of cue variation.

The actual cue parameters of many blind-aid devices represent apparently arbitrary choices on the part of their designers. Few would claim them to be completely "natural cues" and to fully master them a user may require considerable experience. It might therefore be expected that if a long-term user were presented with variations in, or absence of some cues, performance would at least initially be degraded. This could indicate which cues in the display were most significant to the user. If, on the other hand, new combinations of cue parameters were found to result in improved performance then a potential area for improvement of the device would

be uncovered and modifications to the sensory aid should be seriously considered.

The subject used in this experiment was the experienced Sonicguide user referred to in section 5.6:3. A lack of suitable aid users prevented study of a greater number of subjects. A summary of this subject's performance using the "normal" simulation condition and his Sonicguide is found in section 5.6. The shorelining task was used throughout.

6.4:2 Procedure

In the limited time available for testing, it was decided to experiment with three main variations of simulated cues. These were, in order of occurrence;

- (a) Twice normal I.A.D. (Set at 1.0 dB/degree)
- (b) Four times normal I.A.D. (Set at 2.0 dB/degree)
- (c) Zero I.A.D., retaining normal loudness direction cue.

At the beginning of the experiment, 5 trials were recorded with all cues set to the normal values. The variations (a) to (c) were then introduced successively, and 5 trials recorded for each variation, with no practice. After each set of 5 trials, 2 trials were recorded with all parameters reset to normal values.

6.4:3 Results

Figure 6.4 graphs the numerical results of these tests, and shows that an improvement occurred in both RMSDIP and RMSDSL when the I.A.D. was doubled. When it was quadrupled to 2 dB/degree, the resulting RMSDSL value of 2.8 cm was actually superior to average

sighted performance, which yielded 3.2 cm.

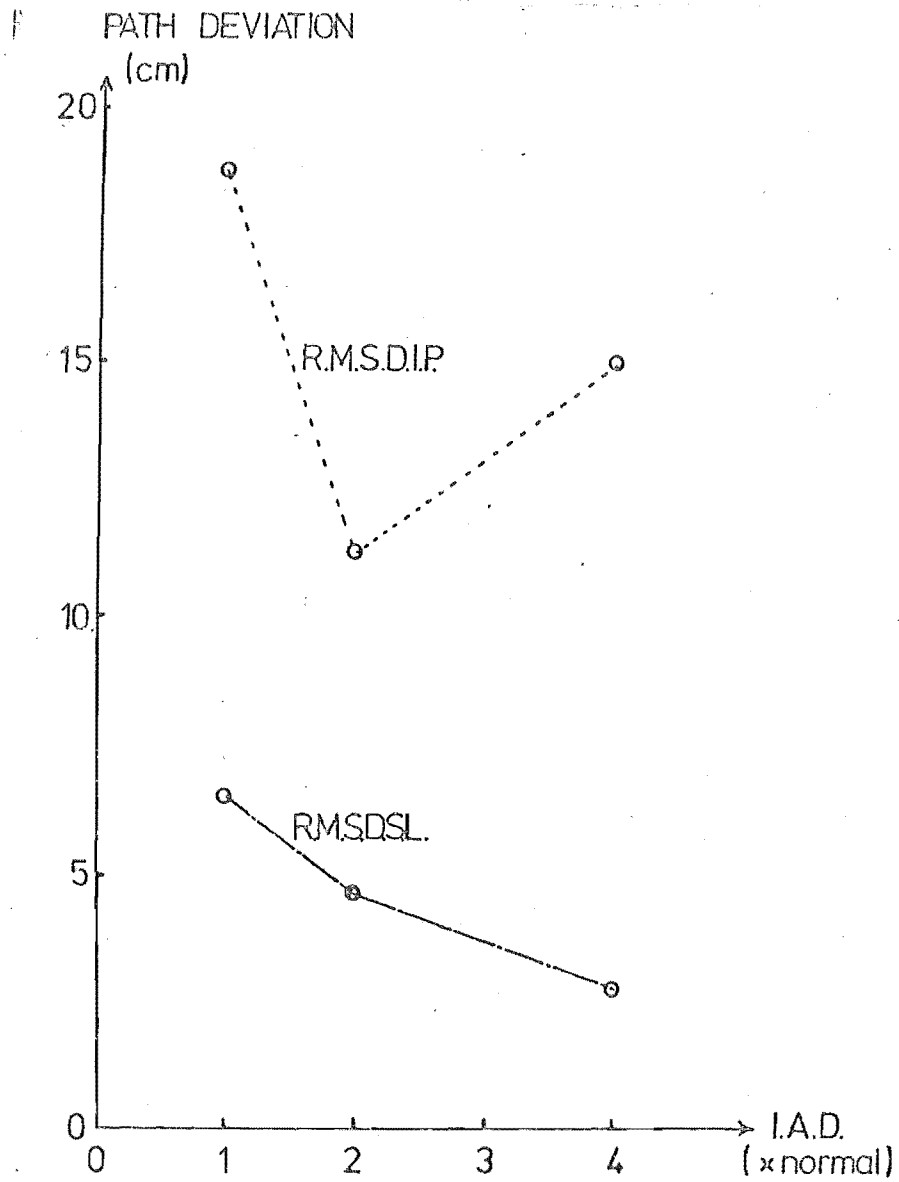


Fig. 6.4: Performance Variation with I.A.D. - Experienced Aid User.

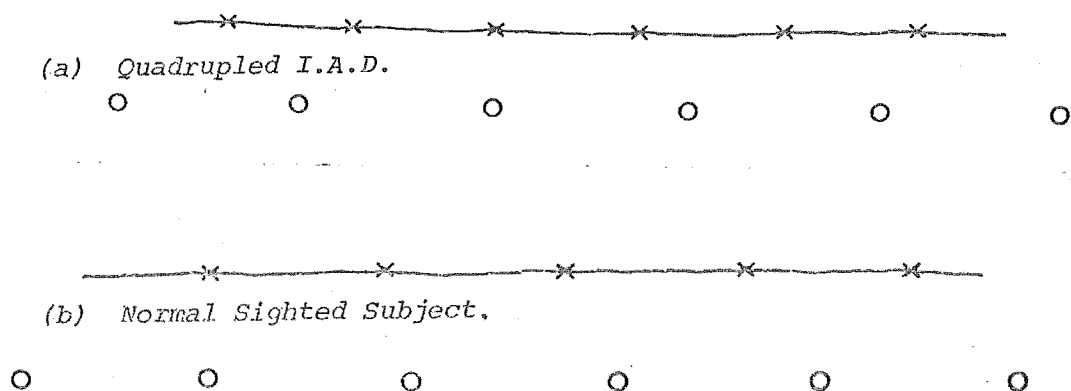


Fig. 6.5 Path Plots.

One-way analyses of variance on the RMSDIP and RMSDSL values across the three conditions of normal, double and quadruple I.A.D. showed significant effects of increasing I.A.D. values ($P < .05$). Thus increasing I.A.D. reduced deviations from the straight path, indicating improved locomotor control. This was most evident in the quadrupled I.A.D. condition, where the RMSDSL value was virtually the same as that for sighted performance.

Figure 6.5(a) illustrates a typical path plot obtained from the quadruple I.A.D. condition, and compares favourably for straightness with the sighted plot of Figure 6.5(b).

During the 2 "normal" trials succeeding each variation condition, performance reverted to much the same level as was achieved both for the ten straight trials previously run under the normal condition, and for the trials performed using the actual Sonicguide. The performance index averages for all the "normal" trials interspersed between the variation conditions are listed in Table 6.3.

TABLE 6.3

*Variation of Performance with I.A.D.
(Experienced Sonicguide User)*

<i>Simulated Condition Performance Index</i>	<i>"Normal" (Mean of Inter- spersed Trials)</i>	<i>Zero IAD Normal "Loudness" Cue</i>	<i>Reduced Range Cue (-10)</i>
<i>RMSDIP (cm)</i>	21.6	12.6	23.7
<i>RMSDSL (cm)</i>	7.5	6.5	12.2

In condition (c) the I.A.D. cue was completely removed, while the normal loudness direction cue remained. Table 6.3 shows that performance in this condition (as indicated by RMSDSL) was comparable to that in the normal condition, although the value of RMSDIP was considerably lower. The latter difference simply reflects the fact that the subject was at a different distance from the poles.

Because of the difficulty of obtaining a smooth fade-out at the edges of the beam using the simulation, the residual loudness cue was slightly greater than that of the commercial sonicguide. Even so, (although more study is needed) the result indicated that good performance is obtainable with only loudness direction cues.

An attempt was made to perform an experiment complementary to the above by removing the loudness cue while retaining the I.A.D. However, removal of any loudness cue within the beam led inevitably to a sharp cut-off at the beam edge (see Figure 6.6), which in itself introduced a new cue because of the well-defined angle at which it occurred. While introduction of this new discontinuous loudness contour led to severe degradation in the subject's performance, it was realised that the condition did not truly represent a zero loudness direction cue, and more thought is needed to produce a meaningful experimental design to test variations in loudness cues.

The final condition of cue variation tested was normal I.A.D. and loudness cues but with range cue reduced by a factor of 10. The resulting numerical performance indices are listed in Table 6.3. As might be expected, some degradation in performance did occur. Considering, however, the large change in range code

involved in this condition, the performance loss was not dramatic, and would suggest that small variations in the range cue are not likely to affect significant improvements or dislocations in the performance of the user.

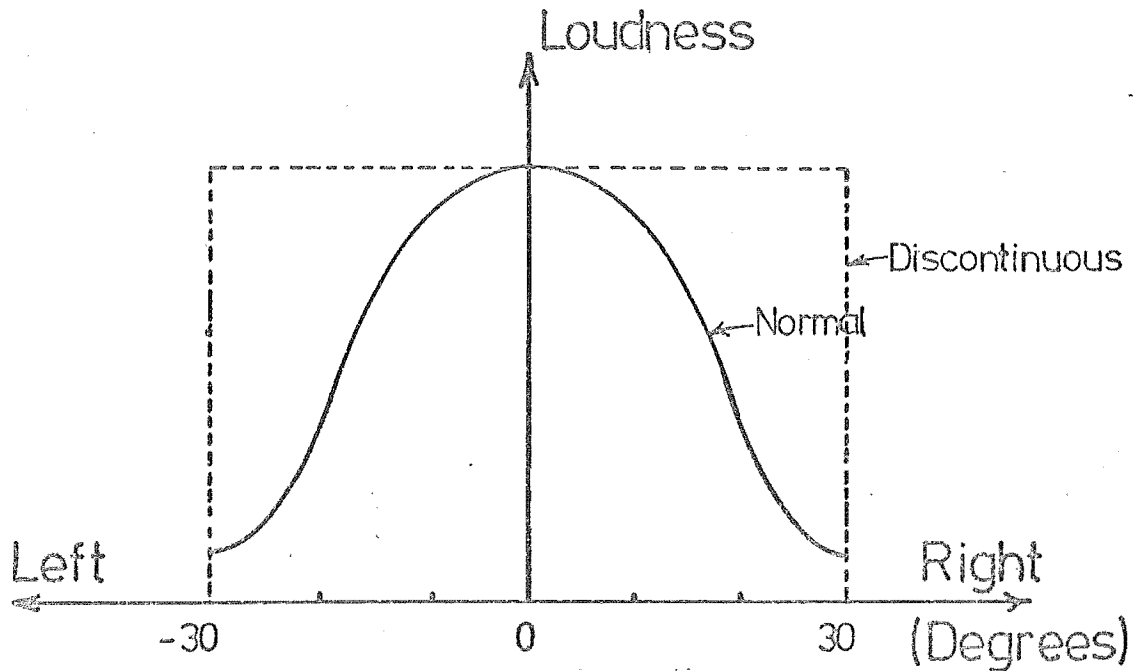


Fig. 6.6.

Effect of Attempt to Remove Loudness Direction Cue

6.5 DISCUSSION.

The studies outlined above suggested that for simple environments the type of simulation facilitated by the computer-linked instrumentation system installed in the Mobility Laboratory is valid as a design aid and analysis tool.

The major question raised by the study was whether or not the I.A.D. cue of the Sonicguide is optimal as it stands. The

subject of interaural amplitude and time differences has been studied by several workers (3,4,5).

In the case of the Sonicguide design, research by Rowell (6) was mainly directed towards finding that I.A.D. characteristic which matched natural auditory localization. These "natural" I.A.D. characteristics were found to involve very small differences in amplitude (of the order of 0.25 - 0.3 dB/degree), to vary considerably between subjects (0.1 - 0.8 dB/degree), and to be dependent upon frequency. It must be remembered that in nature these I.A.D. cues are supplemented by the time difference cues, not present in the Sonicguide. Keith (7), examining adaptation to various values of I.A.D., found that seated subjects could learn to localise accurately with either 0.25 or 1 dB/degree, while some tendency towards greater accuracy and speed of learning appeared under the exaggerated I.A.D. condition. However, he still recommended that transducer splay angles be set at a low value (5°) in order to match the natural localisation function of the ear. It was argued by Kay (3,8) that an increased value of I.A.D. should be used to allow better discrimination and separation of targets in auditory space. In the early evaluation programme of the Binaural Sensor in the United States, some devices were initially found to possess insufficient I.A.D., while some subjects on first exposure to the present commercially produced device are hard pressed to detect any direction cue, which is tolerated to vary between 0.3 and 0.5 dB/degree.

The views of Rowell, Keith and Kay led to the adoption by the manufacturer of this I.A.D. cue.

The present study, which was the first reported investigation of I.A.D. to be carried out using mobile subjects, suggests that there

may be some value in increasing still further the I.A.D. cue of the present device or at least not letting it fall below 0.5 dB/degree.

The limitations of the simulation study preclude making unreserved recommendations - only one task was investigated (although a representative one in terms of electronically aided blind mobility), and the simulation showed some differences from the real device.

However, the results obtained by simulating increases in I.A.D. suggest the value of further investigation in this area, and possibly the modification of a real device for field testing in a complex environment.

Apart from the psychological factors involved in making a decision concerning the optimal I.A.D. characteristic, practical engineering considerations dictate that a large I.A.D. is easier to produce accurately. The I.A.D. is obtained by splaying apart the two receiving transducers and it can be shown (8) that manufacturing tolerances have much more severe effect on the interaural differences at low splay angles (small I.A.D.) than at larger splay angles.

REFERENCES

- (1) "Discussion Including Additional Discussion of All Papers in the Evaluation Session". In R. Dufton (Ed.), Proc. Conf. on Sensory Devices for the Blind, pp 209-211, London: St Dunstan's, 1966.
- (2) Kay, L.; "Sonic Glasses for the Blind : A Progress Report". AFB Research Bulletin, 1973, 24, 25-58.
- (3) Mills, A.W.; "Auditory Localization". In J.V. Tobias (Ed.), Foundations of Modern Auditory Theory, Academic Press, N.Y., 1972, 303-348.
- (4) Hatter, E.R., Carrier, S.C.; "Binaural Interaction in Low Frequency Stimuli : The Inability to Trade Time and Intensity Completely". J. Acoust. Soc. Am., 1972, 51, 6, 1852-1862.
- (5) Mills, A.W.; "Lateralization of High Frequency Tones". J. Acoust. Soc. Am., 1960, 32, 132-134.
- (6) Rowell, D.; "Auditory Display of Spatial Information". Ph.D. Thesis, University of Canterbury, 1970.
- (7) Keith, W.J.; "Adaptation to Distortion of Auditory Space". M.A. Thesis, University of Auckland, 1971.
- (8) Kay, L.; "The Design and Evaluation of a Sensory Aid to Enhance Spatial Perception of the Blind". Unpublished Report, 1973.

CHAPTER 7

CONTEXT OF PERFORMANCE VARIATIONS7.1 INTRODUCTION.

In previous chapters, a series of quantitative results has been reported for subjects performing controlled environment tasks under different conditions of sensory input. A remaining problem at this stage in the experimental program was to classify these sensory input conditions in a hierarchy or progression of possible performance levels ranging from "ideal" normally-sighted performance to "random" performance - performance based on a minimum of spatial cues. For example, it was shown in chapter 4 that using the technique developed therein it was possible to distinguish easily between the performance of a sighted person and that of a Sonic Glasses user in the shorelining task. In chapter 6, naive subjects were seen to exhibit performance covering a wide range below the level of experienced aid users. It was still necessary, however, to examine the following hypotheses more carefully:

- (a) That the difference between blind-aided and sighted performance was minor compared with the difference between aided and "random" performance;
- (b) That aided blind performance was not markedly better than "random" performance.

Previous results showed that a range of performance was measurable above and below that of, say, an experienced Sonicguide user. This suggested that both the above hypotheses were untenable. However, it was desirable to establish properly the level of "random"

performance - both to resolve these questions and to provide a baseline for other data - and this is done in the present chapter.

Modifications of hypothesis (b) could be used as arguments against electronic mobility aids. The skill of some blind persons using only the "natural obstacle sense" has long been known (1), while under some conditions (mentioned in chapter 2) the performance of electronic aid users has appeared to fall below the level achieved before introduction of the aid. Studies reported in this chapter helped establish the relative positions of aided and unaided locomotion in the performance hierarchy.

Finally, results relating performance under conditions of restricted vision to aided performance are reported. Since the obstacle sense and restricted vision studies were performed as a collaborative program, and will be reported in papers now in preparation, only a brief summary is given here. Emphasis is concentrated on the actual results, to illustrate the wide variation in possible performance under differing conditions of sensory input. A framework is thereby put forward within which performance under specific conditions can be assessed.

7.2 VEERING STUDIES.

7.2:1 Introduction

In an attempt to establish numerical performance index values for "random" performance, experiments were performed in which subjects were asked to walk in as straight a line as possible under blindfold. Earlier studies of the "veering" tendencies of blind and blindfolded persons asked to walk in straight lines have been made (2,3). Naturally, the results of these studies were not couched in terms of the types of performance measures used in the present work, and to obtain the

required data a further set of experiments was therefore necessary.

7.2:2 Method

Because of the relatively short distances involved in laboratory experiments, it was not feasible to employ Cratty's technique (3) of allowing the subject to feel his way along a straight handrail placed in the required direction for a short distance before beginning each trial. Instead, subjects were allowed to orient themselves in the required direction (indicated by a pole at the far end of the room) before lowering their blindfolds and commencing locomotion. Twelve subjects each performed this task six times over a distance of 10 metres. At the end of each trial the blindfold was not removed until the subject had been led back to the starting point.

A further six subjects were employed in a second condition, where they were asked to face away from the direction of travel before lowering their blindfolds, turning through 180° , and walking. This condition should be a more valid control for the experiments involving the use of real or simulated aids in which subjects were always asked to turn through 180° before commencing, orienting themselves by the real or artificial spatial cues provided.

7.2:3 Results

Table 7.1 presents the results of this experiment, in which the values of RMSDIP and RMSDSL are of principal interest - since they quantify deviations from the specified path. For the condition in which subjects commenced at 0° , these values are lower than those for the condition in which subjects commenced at 180° , reflecting the extra difficulty involved in correct execution of the initial turn.

TABLE 7.1
Veering Study Results

Starting Direction Index	0°	180°
AVSP (cm/s)	124.9 (14.4)*	120.0 (16.0)
AVAC (cm/s ²)	42.3 (12.9)	42.0 (7.3)
RMSDSP (cm/s)	13.7 (5.6)	16.0 (6.9)
RMSDIP (cm)	25.4 (12.2)	89.5 (55.4)
RMSDSL (cm)	14.1 (8.0)	36.8 (21.4)
SCURV (rad/m)	.263 (.060)	.367 (.132)

* Between S Standard Deviation σ_{n-1}

These latter results are useful for direct comparison with other data for shorelining and pole approach tasks, since the initial rotation was invariably made a requirement in executing those tasks. Hence values for RMSDIP and RMSDSL of approximately 89.5 and 36.8 cm respectively may be taken as upper limits in tasks involving straight line travel over a distance of 10 metres, when initial orientation is included as a part of the task.

If, then, these results are taken as representing "random" performance, hypothesis (b) above is clearly disproven. Typical measured values of RMSDSL for various electronic aids in the shorelining task (always performed in the "180° start" condition) have ranged from 7 to 14 cm.

Hypothesis (a) also appears untenable, since the lower limits of measured performance for the Sonic Glasses or the Single Object

Sensor (see table 7.5) fall almost half-way between "sighted" and "random" performance. The measured difference between sighted and blind-aided performance cannot merely be waved aside, even in the case of the most skilled performance observed.

Comparison of these results with previous veering data is difficult, since in addition to the differences in modes of measurement, variations in experimental procedure and subject selection were present. Although including initial orientation in the task contributed much to the measured veer, the residual veering observed in the "0° start" condition (a condition perhaps closer to previously reported procedures) indicated that the task of merely keeping to a straight path (once oriented) gave measurable error.

7.3 PERFORMANCE USING "NATURAL OBSTACLE SENSE".

7.3:1 Introduction

A useful intermediate datum point for placing performance results in context, is afforded by the level of skill achieved in simple controlled environment tasks using the natural "obstacle sense" as a source of spatial information. It was predicted that this performance level would lie somewhere between sighted performance and the "random" performance (evidenced in section 7.2) obtained from blindfolded persons with no obstacles in the immediate vicinity. It was of very great interest to discover how performance using this sense compares with that using electronic sensory aids.

A considerable literature exists on the subject of the natural obstacle sense, or "facial vision" (4 - 6), and no attempt at a comprehensive review is made here.

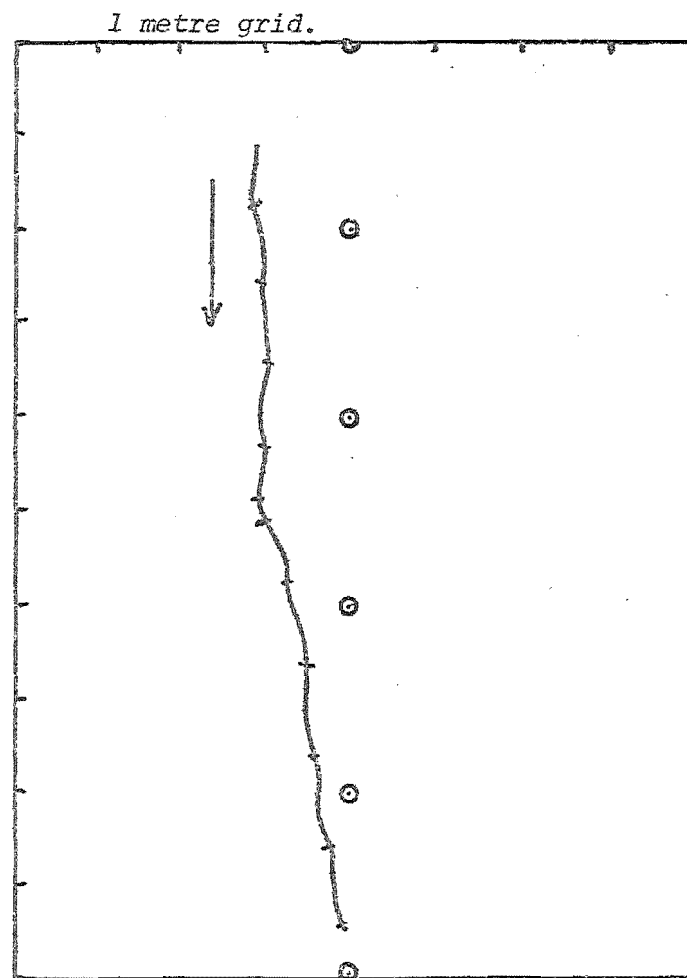
It has been shown (7) that the mean auditory angle subtended by a threshold target is approximately 4.6 degrees (for blind subjects of long experience), indicating that the sense should be usable in mobility by virtue of the typical sizes of some of the objects encountered. Although some experiments (8) have been performed in which subjects approached obstacles and stopped when detection occurred, it was of interest to study, in terms of the measures developed in the present work, the degree to which the obstacle sense would allow subjects to exert continuous control over their bodily paths, as in a shorelining task.

The following represents only a brief summary of ongoing work to indicate where the "obstacle sense" fits into the overall context of locomotor control performance levels.

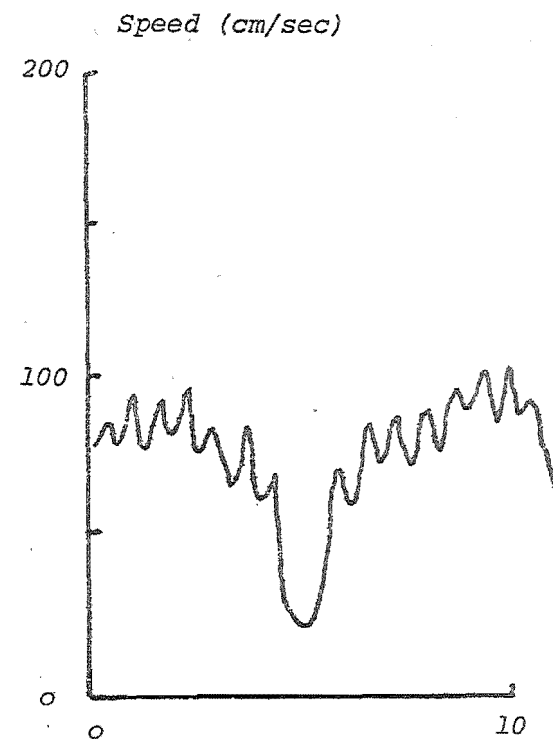
7.3:2 Method

The shorelining task was again chosen for this study. A series of trials spread over several weeks was conducted using one blind subject (a guide dog user) who was known to have a highly developed obstacle sense. Trials were later carried out using six blind and five sighted (blindfolded) subjects.

The arrangement of 1.5 cm diameter poles used in other studies of the shorelining task was deemed unsuitable as providing insufficient area for sound reflections. This was confirmed by the results of a trial performed under these conditions, the path and speed plots for which appear in Figure 7.1. Consequently, an artificial (hardboard) wall, 1.7 m in height, was constructed in the laboratory as indicated in Figure 7.2. A 2 metre wide hardboard path was laid over the carpet alongside the wall to produce good



(a) Path Plots.



(b) Speed Plot.

Fig. 7.1

Attempt to Shoreline 1.5 cm Poles

conditions for footfall sound reflection. Subjects used their normal walking shoes, and were free to click fingers or emit other sounds at will.

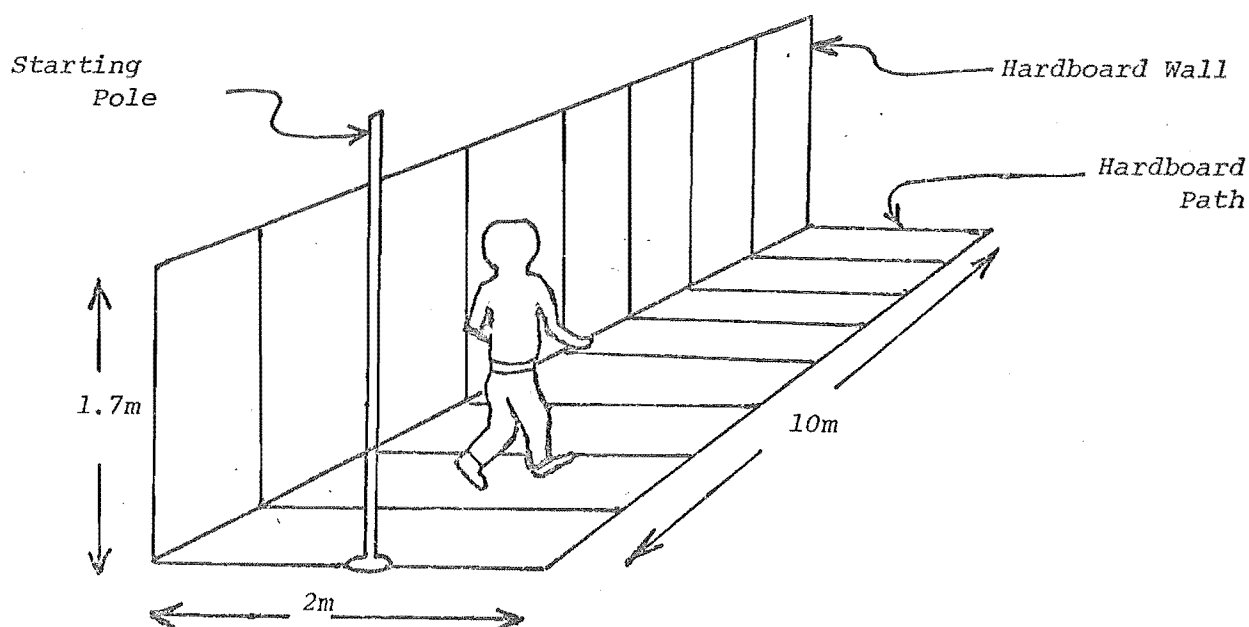


Fig. 7.2
Artificial Wall and Path

In the initial study using the single blind subject mentioned above, six trials were performed in each condition after one practice trial. The experiment was commenced by establishing the subject's performance in the normal wall shoreline condition as described. The wall was then removed, as a control condition. As a further control condition, the wall was replaced, but the subject wore ear muffs and

a blindfold. Next, performance with a blindfold only was investigated, to ensure that residual vision was not playing a major part.

A further set of conditions examined the sensitivity of performance to the disruptive influences of removing part of the wall and introducing masking sounds. The former requirement was filled by removing every second panel (1.2 m wide) from the wall, while the second was filled by turning on the air conditioning fans in the laboratory, raising the ambient noise level (measured on a B. & K. sound level meter) by 22 dB from approximately 35 dBA to 57 dBA.

Finally, the effect of introducing an auditory "aiming point" in the form of a 30 Hz square wave emitted from a loudspeaker placed at the far end of the ideal path at a height of 1.5 metres was investigated, while retaining the presence of the wall.

7.3:3 Results

The results of this experiment are summarized in Table 7.2. Performance in the normal shorelining task (Figure 7.3a) was seen to give RMSDSL values of 10-12 cm, with RMSDIP ranging from 17 to 23 cm. Later trials on subsequent days showed some learning effect and the mean values over all trials in this condition were 9.2 cm for RMSDSL and 18.1 cm for RMSDIP. As expected, the presence or absence of the blindfold had no major effect, as the subject's residual vision was so curtailed that she could only just detect the shining of a powerful torch from a distance of 1 m in a darkened room.

TABLE 7.2

Obstacle Sense : Shoreline

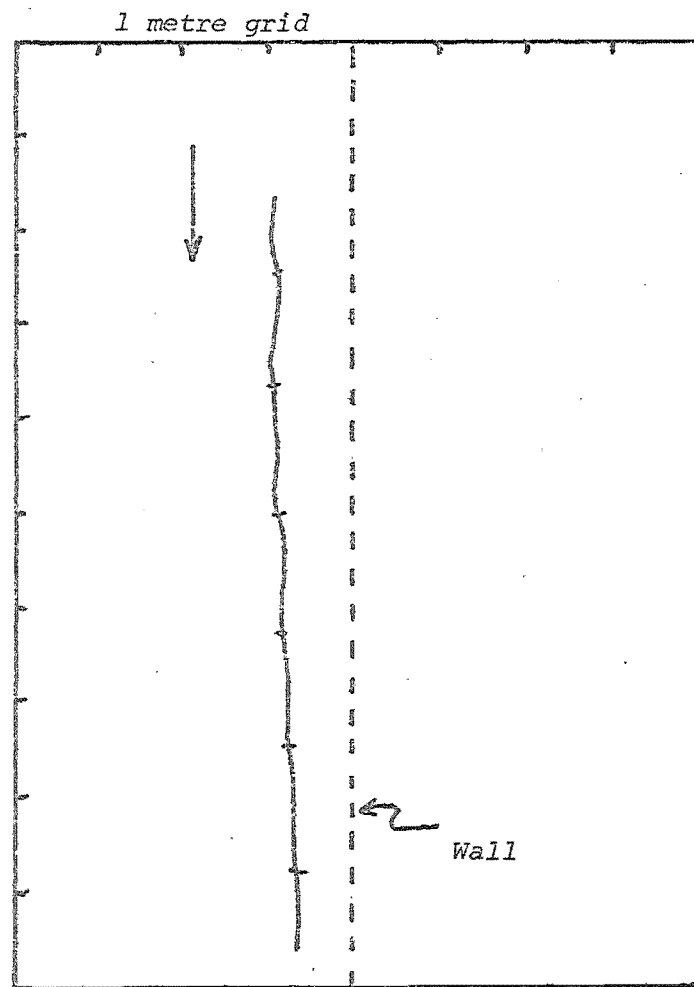
(a)

Condition Index	Shoreline	No Wall	Earmuffs & Blind- folded	Blind- folded Only
AVSP	123.7(2.9)*	120.8(4.7)	107.3(4.0)	118.5(1.8)
AVAC	22.6(3.6)	31.3(6.8)	33.5(6.1)	25.7(2.7)
RMSDSP	7.4(1.2)	11.4(7.5)	12.5(2.1)	7.9(1.1)
RMSDIP	22.4(5.2)	52.7(18.9)	37.2(14.5)	17.7(4.8)
RMSDSL	10.9(4.3)	24.8(8.1)	18.5(8.7)	12.6(4.0)
SCURV	.333(.028)	.399(.088)	.482(.090)	.388(.019)

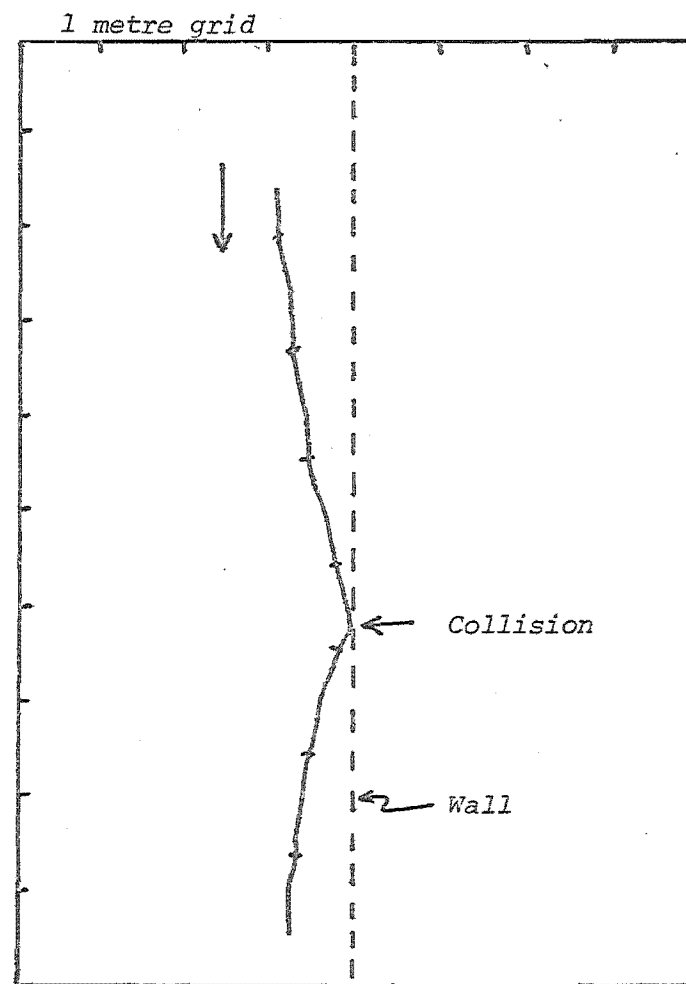
* Std Deviation

(b)

Condition Index	Shoreline Normal	Partial Wall	Masking 30 dB	Target Presence
AVSP	121.7(2.5)	117.2(2.1)	123.6(1.2)	119.2(4.6)
AVAC	24.2(5.5)	30.2(4.5)	22.5(1.9)	30.8(2.6)
RMSDSP	7.4(1.3)	9.5(2.5)	7.8(1.9)	12.2(3.8)
RMSDIP	18.1(8.3)	20.0(9.1)	28.3(8.6)	31.5(8.5)
RMSDSL	6.8(3.0)	13.7(7.7)	15.6(5.9)	12.8(2.5)
SCURV	.359(0.41)	.391(.019)	.357(.027)	.353(.056)



(a) Normal Condition.



(b) Ear Muffs.

Fig. 7.3 Obstacle Sense Shoreline Path Plots.

Removal of the wall severely upset performance, confirming that the relatively good performance recorded above was entirely a function of the wall and not a response to other uncontrolled cues. Similarly, the drastic degradation in performance - including a decrease in speed and a rise in "jerkiness" as well as the expected rise in path deviation measures - which occurred under the earmuff condition confirmed that the task was being performed entirely on auditory spatial information.

Table 7.2(b) illustrates the results of the further investigation of performance sensitivity to disruptive influences. Removal of parts of the wall, with a corresponding reduction in effective reflective area, caused a decline in performance, while the introduction of masking had a strong effect in this direction. The presence of the loudspeaker as a target or aiming point appeared to have a similar effect to the masking sound - performance tending to deteriorate under this condition rather than improve.

Later results from other blind subjects showed average values of path deviations somewhat in excess of those above. The mean-values of RMSDSL and RMSDIP for six subjects in the normal shorelining condition were 13.1 cm and 27.8 cm respectively. Thus the results reported above can be taken to represent relatively skilled performance. The sensitivity of the performance of the six blind subjects to obstacle size was tested in an experiment using a wall, a row of 6 inch diameter poles, and a row of 2 inch diameter poles respectively, as the shoreline. Performance index means for the six subjects, who each performed 6 trials per condition, are given in Table 7.3. A one-way analysis of variance on the RMSDSL measure ($F(2,10) = 3.88, P < .1$) showed that a significant degradation in

performance occurred as obstacle size decreased.

TABLE 7.3

Obstacle Sense Performance : 6 Blind Subjects

<div style="text-align: center;"> <i>Shoreline</i> <i>Index</i> </div>			
	<i>Wall</i>	<i>6" Poles</i>	<i>2" Poles</i>
<i>AVSP</i>	<i>103.0</i>	<i>89.3</i>	<i>89.6</i>
<i>RMSDIP</i>	<i>27.8</i>	<i>35.6</i>	<i>36.1</i>
<i>RMSDSL</i>	<i>13.1</i>	<i>22.2</i>	<i>23.0</i>

Finally, the results of tests in the shorelining task using naive blindfolded sighted subjects yielded an average value for RMSDSL of 20.6 cm. It should be noted that while their performance was considerably inferior (without training) to that of the experienced blind subjects, it was still superior to that achieved under similar conditions but in the absence of the wall (the 180° condition of Table 7.1). Thus the presence of the wall had some effect even though the subjects were not accustomed to frequent use of the obstacle sense.

In summary, it can be seen that under ideal conditions as provided by the large soundproofed laboratory with very low ambient noise level, large wall, and hard path surfaces, performance of experienced subjects using the obstacle sense as the principal source of spatial information for locomotor control can be relatively good, although results fall well short of sighted performance. Naive

subjects fare much more poorly, while performance appears to be very sensitive to disruptions such as increases in ambient noise, and reduction of obstacle size.

Apparently under the ideal conditions mentioned, obstacle sense performance in shorelining a wall can sometimes approach the level of experienced Sonicguide user performance shorelining a row of poles (section 5.6:3). In comparing the two, however, it should be realized that the pole task cannot be performed at all using the obstacle sense, while the exact nature of a shoreline (whether wall, trees, or poles) makes much less difference to a Sonicguide user. Also, the sensitivity to masking sounds should not be present to the same extent using a suitable artificial auditory display, as the signal level can be increased so that the signal to noise ratio remains constant.

7.4 PERFORMANCE UNDER CONDITIONS OF RESTRICTED VISION.

7.4:1 Introduction

A further method of placing locomotor control measurements in context is the investigation of degraded visual input as the basis for spatial orientation. In principle it should be possible to assess the nature and extent of the gulf between sighted performance and blind aided performance in controlled environment tasks by progressively restricting a sighted subject's vision until performance declines to blind-aided levels. The nature of the restriction required to achieve this might also shed some light on the functional deficiencies of existing mobility aids.

7.4:2 Method

One method of restricting visual information - the use of a translucent face mask - has already been described (section 4.7:4) and found to produce a degradation of performance in the target approach task, comparable to that observed when the task is performed under auditory control. This method of vision restriction was found to be unsuitable for the performance of other more complex tasks, and since it produced such a severe reduction in range and direction information available to the subject, it was not thought to constitute the most convenient possible analogy to an ultrasonic mobility aid.

In attempting to produce a visual analogy to an auditory display such as that of the Sonicguide, the principal features to reproduce were felt to be the outward flowing pattern of the spatial field as the user moves past obstacles (reproduced both in normal vision (Gibson) and in the Sonicguide display), the restriction of range and possibly beamwidth, together with consequent omission of background information.

A possible solution was found in the form of a beam of ultraviolet light emanating from a head-worn lamp. Using this apparatus in the darkened laboratory, it was possible to remove background information by coating with suitable reflective paint only those objects which were to be visible when the beam of ultraviolet light was pointed at them. A number of poles were treated in such a manner and used to form a shoreline in the usual arrangement of Figure 5.11. The beamwidth of the device was controlled relatively easily by collimating the light to a greater or lesser extent, very narrow beams being achieved by shining the light through a bundle of drinking straws. The range could be controlled to some degree by varying the

intensity of the ultraviolet source. It was found that using a 30° - 60° beamwidth, shorelining performance could be degraded to the levels achieved by relatively unpractised Sonicguide users.

A 2 x 2 experiment was designed using two tasks - target approach and shorelining - and two levels of information input - normal vision (background included) and UV lighting (background excluded). From informal observations it was suspected that sighted persons treat a shorelining task to some extent as a target approach task, concentrating more on aiming towards some distant point than on monitoring carefully the immediate part of the shoreline. It was therefore expected that the pole approach task might not show as much difference in performance between "normal" and "no background" illumination conditions as the shorelining task.

Each of 6 subjects performed the four tasks six times in different orders. As a precaution the UV headgear was worn in both illumination conditions.

The ultraviolet illumination used gave a wide beam (approximately 90 degrees) and an effective range of approximately 4-6 metres so that in most cases in the shorelining task the 2 or 3 closest poles could be seen. Thus the overall "field of view" was slightly larger than that of the Sonicguide. Because of the range restriction in the ultraviolet illumination, the "no background" condition for the pole approach task was achieved by mounting a low intensity light on the pole.

7.4:3 Results

Table 7.4 displays the results of the study in terms of the indices RMSDIP and RMSDSL, the factors of major interest. A two-way analysis of variance showed that there was a significant overall effect ($P < .05$) between the two illuminations indicating that performance under the "no background" conditions was poorer for both tasks. Also performance in the shorelining task was significantly ($P < .05$) poorer than that in the pole approach task. This reflected the greater difficulty of the shorelining task, which appeared to be the more severely affected by lack of background information.

TABLE 7.4

Degraded Visual Information: Shorelining Performance

(a) RMSDIP (cm)	Pole Approach	Shorelining
Normal Light	7.2	8.7
Dark (No Background)	9.0	17.2

Analysis of Variance:

Shoreline/Pole Approach ($F(1,5) = 11.33$; $P < .05$)

Normal Light/Dark ($F(1,5) = 7.38$; $P < .05$)

(b) RMSDSL (cm)	Pole Approach	Shorelining
Normal Light	2.9	3.7
Dark (No Background)	4.4	8.0

Analysis of Variance:

Shoreline/Pole Approach ($F(1,5) = 17.6$; $P < .01$)

Normal Light/Dark ($F(1,5) = 14.3$; $P < .05$)

The results suggested that performance of either task is easier when something more than the actual shoreline can be perceived. It is felt that this result could have implications for mobility aid design, and may provide an argument in favour of a true "environmental sensor" rather than a more restricted obstacle detector-type of device.

Results of further experimentation will be reported elsewhere, clarifying the exact nature of the background information which accounts for the difference in shorelining performance between the "background" and "no background" conditions.

An interesting outcome of the experiment is that shorelining performance with no background information was remarkably similar to experienced Sonicguide user performance in the same task. Comparison of tables 7.4 and 5.1 shows that RMSDIP values were 17.2 and 16.8 respectively, while RMSDSL values were 8.0 and 7.7 respectively. Thus an experienced user of the auditory display, receiving information on the range and azimuths of shoreline components could perform as well as subjects receiving similar information visually. This might tempt the conclusion that the Sonicguide display cannot be improved further (in terms of allowing accurate spatial orientation and locomotor control) without introducing some additional background information, as in the visual analogy. However, this conclusion has already been proven false. It was shown in section 6.5 that such an improvement is possible, merely by altering emphasis on existing cues. Possibly, exaggeration of visual cues (using lenses) might produce a similar effect! Whatever the implications, however, the immediately important result is the proven possibility of investigating a continuum of performance levels between the blind-aided and sighted, by adjusting visual and/or mobility aid cues. This

should hold promise in future locomotor control research, and enable the remaining differences between blind and sighted performance to be more thoroughly investigated.

7.5 CONCLUSIONS.

An attempt has been made to place measured performance of controlled environment tasks - particularly the shorelining task - into perspective. Approximate datum lines have been established at the extremes of sighted and "random" performance, and a framework has been built within which the relative capabilities of respective devices can be objectively compared. These comparisons would be made in terms of an aid's ability to allow accurate spatial orientation and locomotor control.

On the basis of the above results, a tentative classification of spatial orientation and locomotor control skills (Table 7.5) may be drawn up. Further research is desirable to validate these tentative conclusions and insert more data from users of long canes, guide dogs and other mobility aids. While the limitations of such a classification must be borne in mind (such as attention being concentrated on a subset of mobility skills), the present results are felt to represent some advance in the establishment of an objectively-measurable performance hierarchy.

TABLE 7.5

Straight Line Tasks : Hierarchy of Performance

Condition	No. of Subjects Tested	Performance (RMSDSL approx. mean)
Sighted (Target Appr.)	12	3
Simulated Sonicguide, Experienced User, Enhanced Direction Cue (Shoreline)	1	3
Sighted (Shoreline)	12	3.5
Reduced Vision - No Background (Target Appr.)	6	4.5
Experienced Sonicguide/S.O.S. (Shoreline)	2	7
Reduced Vision - No Background (Shoreline)	6	8
Auditory Control (Target Appr.)	12	9
Naive Subjects - Real/Simulated Sonicguide/S.O.S. (Shoreline)	15	12
Nat. Obs. Sense - Blind <u>S</u> 's (Shoreline)	6	13
Veering - 0° Start	12	14
Nat. Obs. Sense - Naive <u>S</u> 's (Shoreline)	5	20
Nat. Obs. Sense - Blind <u>S</u> 's 6" dia. Poles (Shoreline)	6	22
"Random" - Veering (180° Start)	6	36

REFERENCES

- (1) Supa, M., Cotzin, M., Dallenbach, K.; "Facial Vision : Perception of Obstacles by the Blind". Am. J. Psychol., 1944, 57, 2, 133-183.
- (2) Howard, I.P., Templeton, W.B.; "Human Spatial Orientation". London: Wiley, 1966.
- (3) Cratty, B.J.; "The Perception of Gradient and the Veering Tendency While Walking Without Vision". AFB Research Bulletin, 1967, 14, 31-52.
- (4) Worchel, P., Dallenbach, K.; "Facial Vision : Perception of Obstacles by the Deaf-Blind". Am. J. Psychol., 1947, 60, 4, 502-553.
- (5) Cotzin, M., Dallenbach, K.; "Facial Vision: The Role of Pitch and Loudness in the Perception of Obstacles by the Blind:." Am. J. Psychol., 1950, 63, 4, 485-515.
- (6) Ammons, C.H., Worchel, P., Dallenbach, K.; "Facial Vision : The Perception of Obstacles Out of Doors by Blindfolded and Blindfolded-Deafened Subjects". Am. J. Psychol., 1953, 66, 4, 519-553.
- (7) Rice, C., Feinstein, S., Schusterman, R.; "Echo Detection Ability of the Blind - Size and Distance Factors". J. Experimental Psychology, 1965, 70, 246-251.
- (8) Beurle, R.L.; "Electronic Aids for Blind People". British Journal of Psychology, 1951, 42, 164-171.

CHAPTER 8

FURTHER APPLICATIONS OF SIMULATION AND EVALUATION METHODS

8.1 INTRODUCTION

In preceding chapters, some of the basic problems of objective mobility research (and, in particular, locomotor control), have been resolved. It has been shown that it is possible to make quantitative distinctions between levels of locomotor control performance achieved using different types and degrees of sensory input. The feasibility of dynamic simulation of mobility aids has been established, and an overall scale for comparison of different levels of performance has been determined. Thus a wide and relatively unexplored field of research has been opened up, and the present chapter briefly describes just a few possible applications of the techniques described above.

8.2 TACTILE DISPLAY SIMULATION

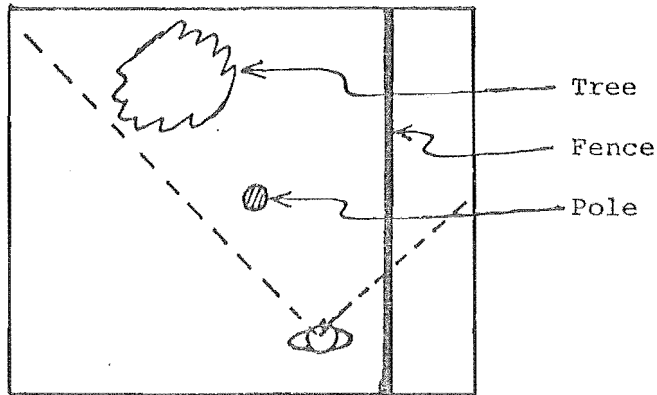
8.2:1 Introduction

Some success has been achieved by Collins, Bliss and others (1 - 8) in the use of tactile displays for the blind - more especially for vocational and reading applications. Using such systems, containing up to 1000 individual electrocutaneous stimulating elements driven from a television camera, subjects have been able to distinguish shapes and even operate oscilloscopes by observing displayed waveforms (1).

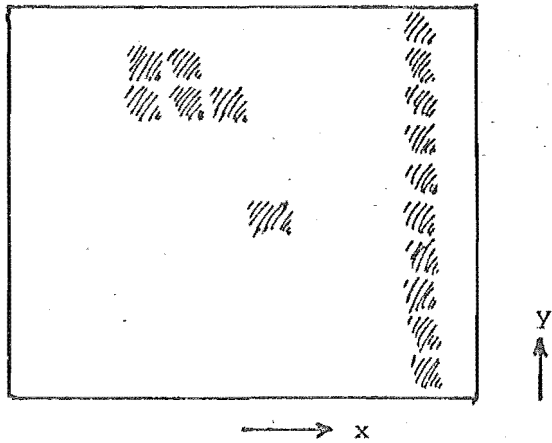
However, one area in which present systems have achieved only limited success is that of mobility. While television camera-driven systems (4) have shown some promise in this application, some of their shortcomings are evident from a consideration of the type of tactile picture they present to the user. For example, if the user is approaching a large wall, all stimulators will be operating fully regardless (within limits) of his distance from the wall. There is, in this and other situations, no readily interpreted range cue to warn him of imminent collision. Relatively high powers of resolution are necessary before range information can be reliably obtained from an "elevation" type view of the environment as provided by television camera systems.

It was proposed by Kay that a "plan" - type view of the environment in front of the blind user would provide, more directly, the range and direction information thought to be vital for mobility. The system would be designed so that objects distant from the user stimulated elements near the bottom of the tactile array (which is worn on the stomach) while closer objects stimulated elements nearer the top.

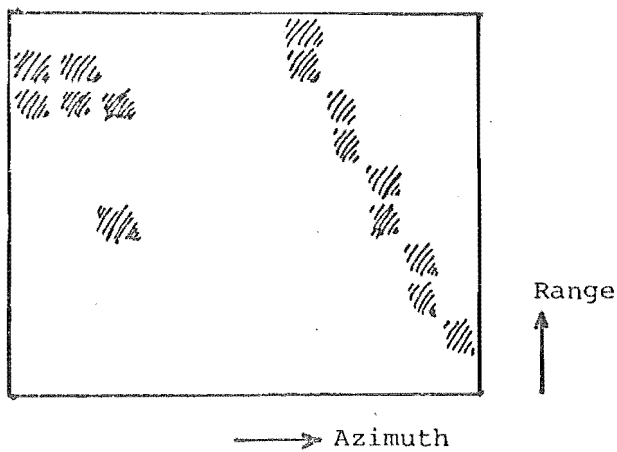
Such a display could be realized by substituting an air sonar for the television camera. More than one alternative exists for the configuration of the sonar - tactile array interface. One method would be to produce a one-to-one mapping of the environment on the array of stimulators, in a manner similar to a P.P.I. radar display (Figure 8.1). Alternatively, each row of stimulators could be used to represent an increment in range, which each column represented an increment in azimuth. This would produce the distorted type of



(a) Original Scene



(b) "PPI" Display

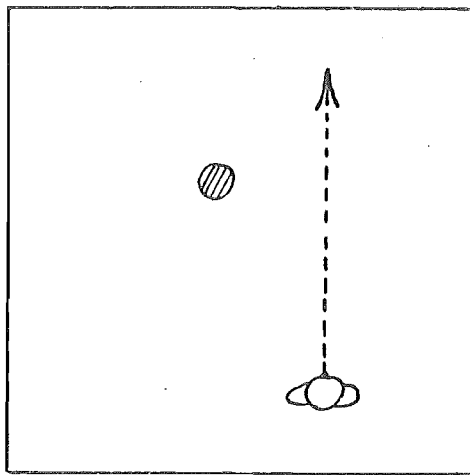


(c) "Range-Azimuth" Display

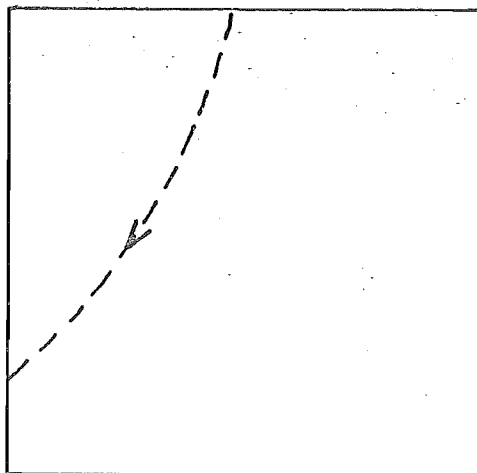
Fig. 8.1

Possible Forms of Display.

tactile picture shown in Figure 8.1c. The latter configuration would be simpler to implement using existing regular rectangular tactile arrays, while a possible advantage would be production of an accelerating outward flow pattern (analogous to that experienced under visual conditions (9, 10)) as the subject moves closer to and passes alongside objects. For example, illustrated in Figure 8.2, is the trajectory of a telegraph pole image on the display as the subject passes it along a footpath.



(a) Pedestrian Passing Pole



(b) Flow Pattern on Range-Azimuth Display.

Fig. 8.2

Range - Azimuth Display Flow Pattern.

A proposal for an experimental prototype of such a display system is illustrated in Appendix 3.

In order to test the feasibility of such a display, an experiment was performed using the mobility aid simulation system described in chapter 5.

8.2:2 Simulation System Modification

The tactile display used for the experiment was kindly lent by the Smith Kettlewell Institute of Visual Sciences, and consisted of an array of mechanical (vibrating) stimulators with row and column switching circuitry designed to be driven by a video signal from a T.V. camera. The switching circuitry clocked through the elements, gating each one in turn, at a rate of 2.5 kHz, representing a frame rate of 25 Hz . Scanning was horizontal, and in order to activate a particular stimulating element a video pulse was required during the time when that element was enabled.

To use the range and direction information from the objects in the laboratory, modifications to the mobility and simulation software were required. This enabled the decision as to which array elements, if any, it was desired to stimulate. Also, video pulses had to be generated at the appropriate times in synchronism with the clock internal to the tactile display unit. The main constraint on the overall system was that of digital computing speed, since real time operation was required. The method adopted for production of the video signal left the computer free for other operations except for 3 uses per update of the display (occurring, as before, approximately 10 times per second).

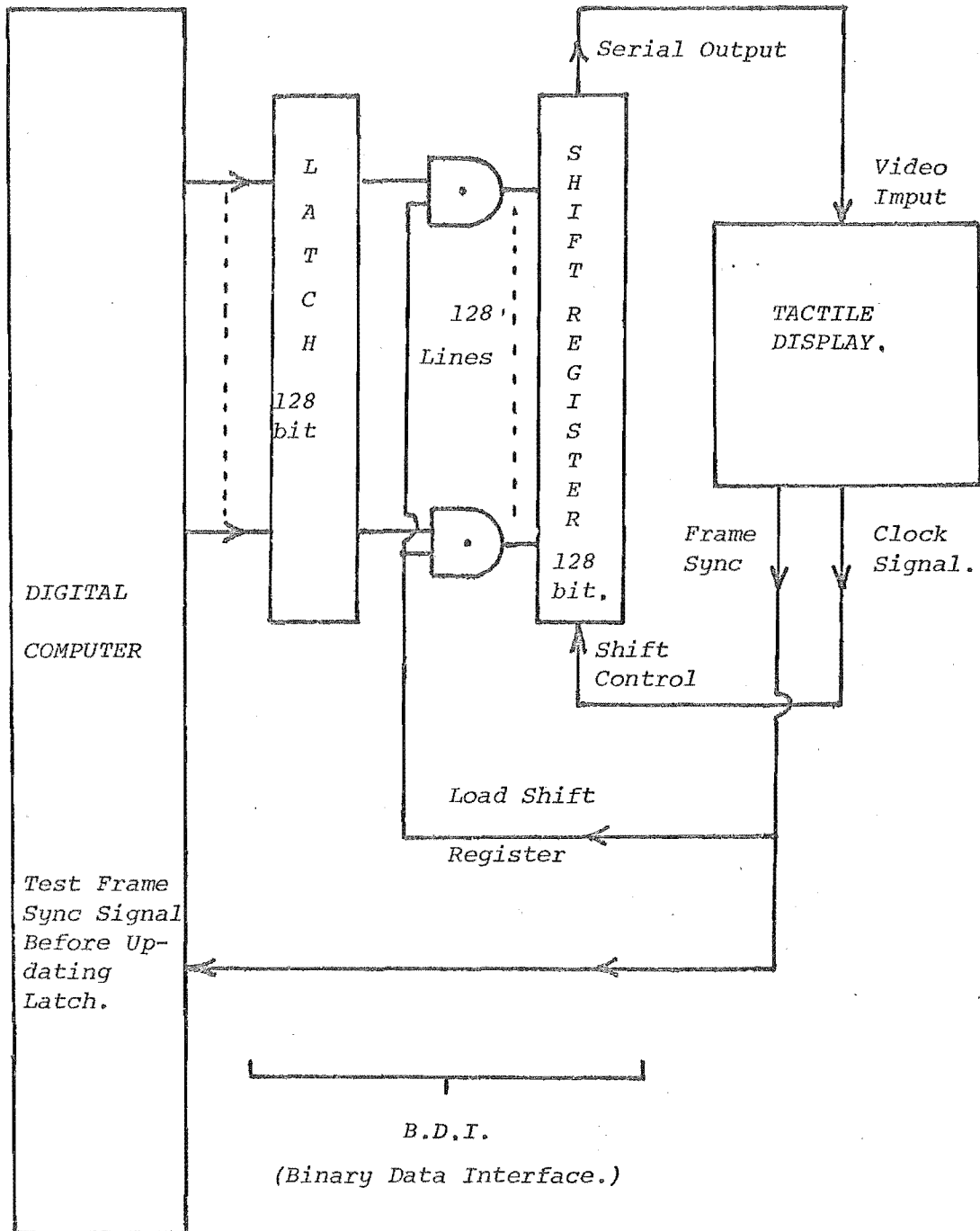


Fig. 8,3

Interfacing Digital Computer to Tactile Display.

This was accomplished using the special binary data interface with which the computer was equipped. The interface was used as a 128 - bit shift register, the contents of which were clocked into the tactile display video input by the display's own clock (Figure 8.3). The shift register was reloaded at the end of each frame from a 128 - bit latch, the transfer being controlled by the end-of-frame pulse generated by the display's internal scanning circuitry. The contents of this latch were updated periodically by the digital computer, according to the pattern it was desired to create on the display at the time. In this way the display frame rate were entirely independent, the former being in fact variable for the reasons stated in chapter 5. Before each update of the latch, the "end of frame" signal was tested to ensure that the updating operating did not interfere with the transfer of data to the shift register.

Computation of the required pattern to be presented to the display, and the conversion to an appropriate bit sequence for video signal generation via the shift register were performed using assembly-language subroutine.

The particular display specification adopted was that of Figure 8.1b with each column of stimulators representing an azimuth quantum and each row representing a range quantum. Zero range was specified as the top edge of the display, worn on the stomach. Maximum range was 3m, and beamwidth 60° . Only the nearest target within the "beam" of the stimulated sonar was displayed, and a target stimulated only one vibrating element at a time.

8.2:3 Experimental Testing

Mobile testing on a blindfolded subject was carried out under rather difficult conditions, as the experimental display unit used

was not designed for portability. The switching and driving circuitry for the mechanical stimulators was contained in a large, heavy suitcase which it was necessary for the subject to carry. He also had to hold the tactile array itself - also a heavy unit - against his abdomen with his free hand.

No difficulty was experienced in walking up to a pole and nudging it using the device, and it was decided to perform a series of trials on the shoreline task, laid out in the familiar configuration of Figure 5.11. After one practice trial, ten runs were recorded. Plots of the subjects trajectory on trials 1,5, and 10 appear in Figure 8.4 (a, b, and c). For comparison, examples from an experienced sonicguide user are reproduced in Figure 8.5.

Numerical performance indices for the above three trials appear in table 8.1, in which steady improvement is evident over the trials. By the last trial the performance (eg. in terms of RMSDSL) compared favourably with results obtained from unpractised subjects using other aids and subjects using simulated aids (tables 7.5, 6.1). An RMSDSL value of 10.6 was exceeded in the occasional trial even for an experienced sonicguide user. It would be unreasonable to expect performance to approach its potential final standard after so few trials. It should also be noted that the need to carry a heavy load undoubtedly both slowed the subject down and caused more side-to-side lurching than would otherwise have occurred. This materially increased the values of SCURV and RMSDSL.

A second task performed by the subject was to slalom between the 6 poles constituting the shoreline for the previous task. The slaloming task is moderately difficult, and to make the condition even more stringent no practice was allowed. Figure 8. 6 (a, b) illustrates the subject's trajectory in the first and third trials.

Only three trials were performed in this condition owing to the subject's state of physical exhaustion. Again, a plot obtained from an experienced sonicguide user is shown in Figure 8.6 (c) for comparison. By the third trial, performance was surprisingly good.

TABLE 8.1

Tactile Display Shorelining Performance.

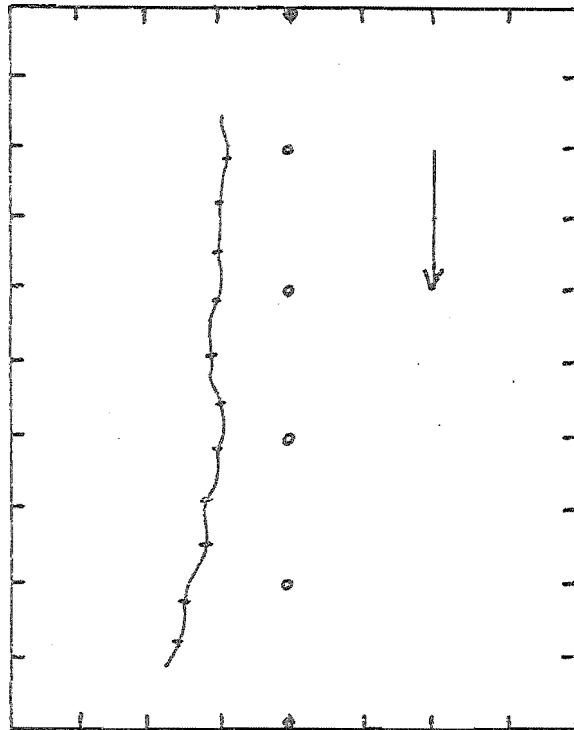
	Trial 1	Trial 5	Trial 10
AVSP (cm/sec)	90.5	99.4	114.3
RMSDSL (cm)	22.3	16.7	10.6
CURV (rad/m)	1.056	.823	.560

AVSP = AVerage SPeed

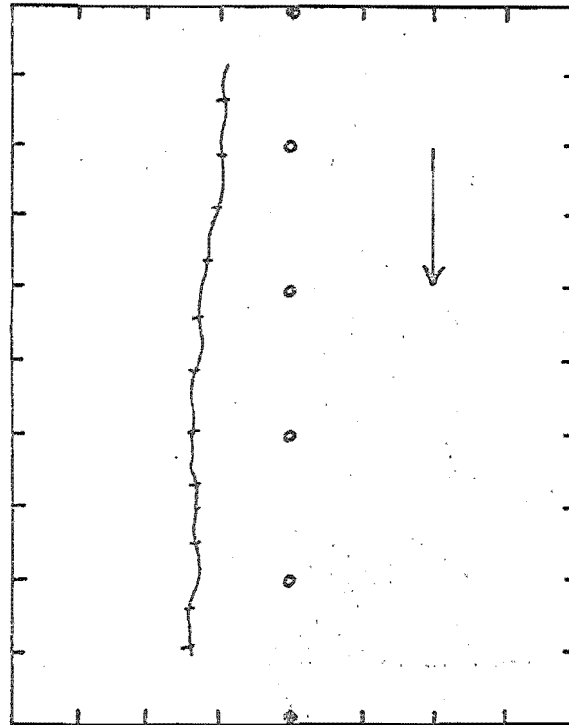
RMSDSL = RMS Deviation from a Straight Line

CURV = Mean Curvature of Path

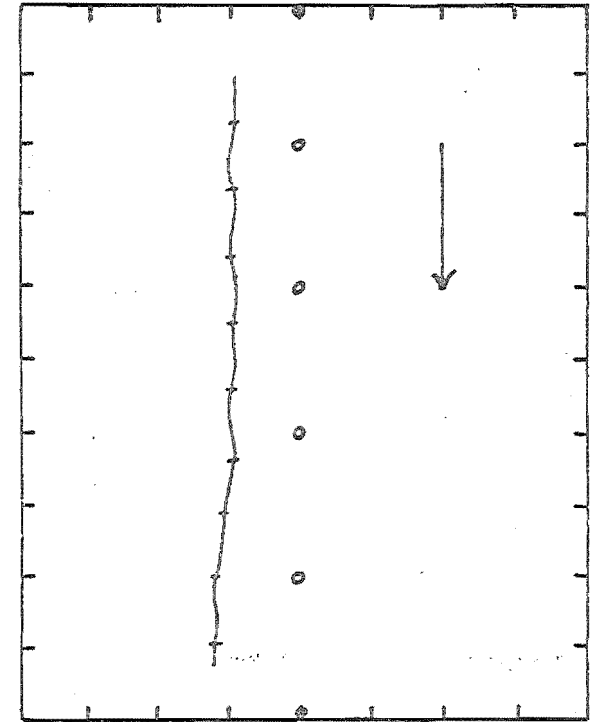
1 metre grid



(a) Trial # 1



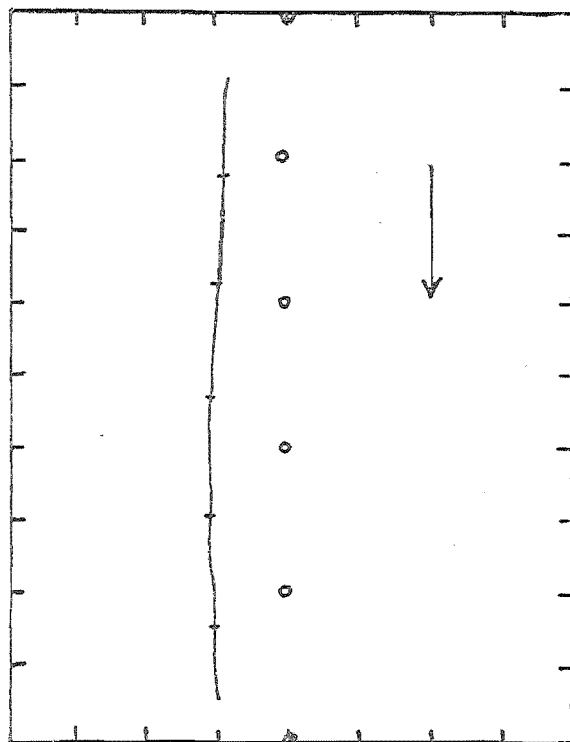
(b) Trial # 5



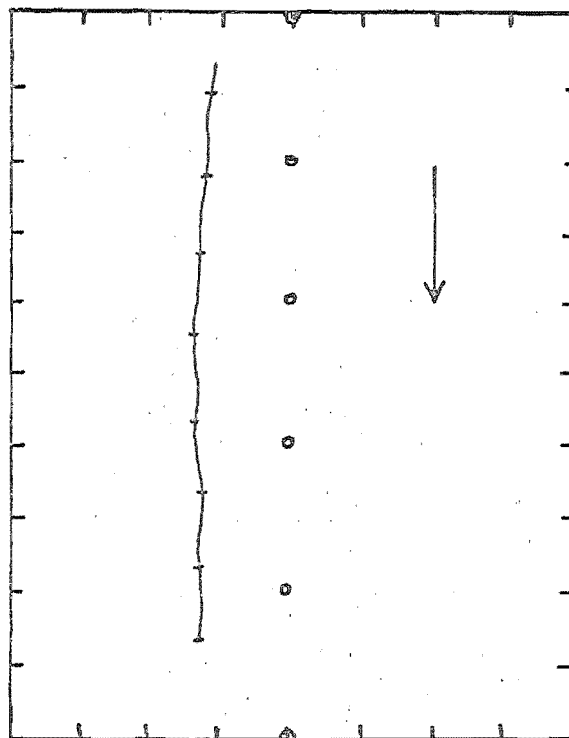
(c) Trial # 10

Fig. 8.4
Tactile Display Shorelining Results.

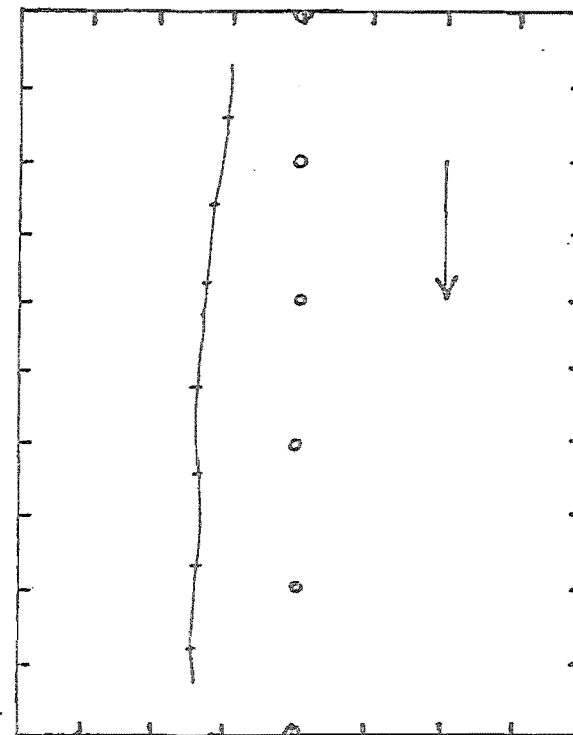
1 metre grid



(a)



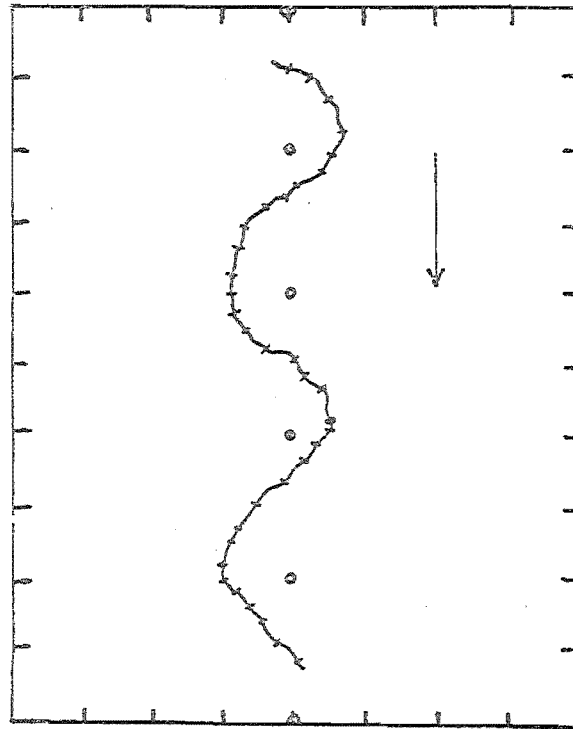
(b)



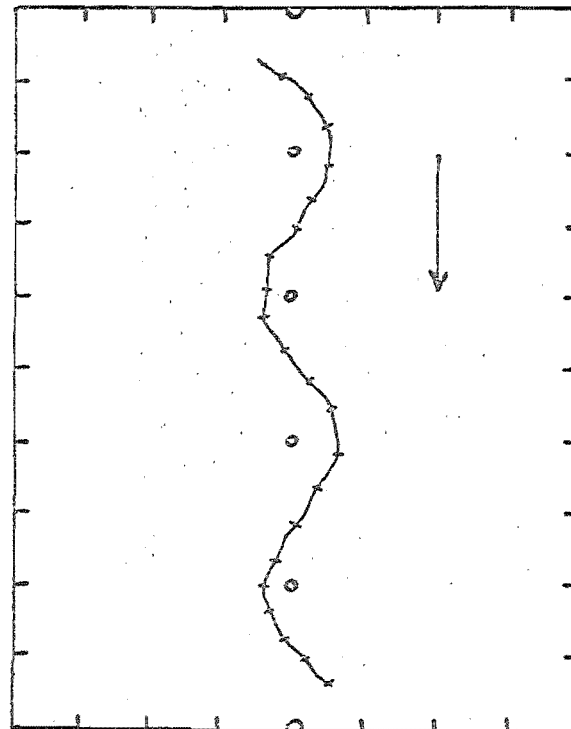
(c)

Fig. 8.5
Sonicguide User Shoreline Performance.

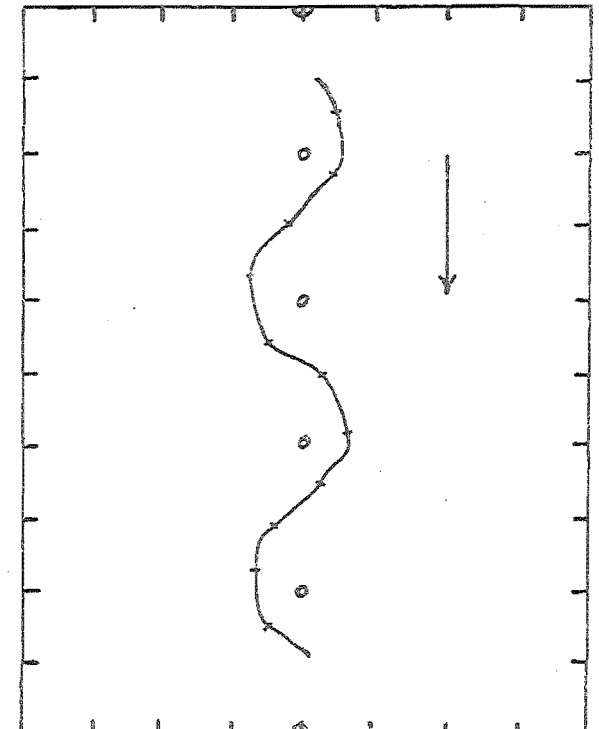
1 metre grid



(a) Trial # 1



(b) Trial # 3



(c) Experienced Sonicguide
User

Figure 8.6: Slalom Performance.

8.2:4 Discussion

A tactile display system using the type of information obtainable from a sonar was concluded to be promising from the point of view of enhancing blind mobility. No evidence was obtained regarding the difficulty of the shorelining and slaloming tasks using a television camera based system, but it is felt that avoiding pole collisions may have been difficult, at least in the slalom task. The subject tested here was confident about his knowledge of when he was or was not about to collide with a pole, as the display gave a good, explicit idea of the range of a target. In fact the whole experiment was carried out without a single collision.

Much further work remains to be done in researching tactile displays for mobility, including making a decision on the relative merits of the two directional coding schemes of Figure 8.1 (b and c). Further simulation studies must be dependent on the availability of a more readily portable device. Study of such tasks as approaching walls using T.V. and sonar systems would be informative, whilst the subject in the above experiment felt that the tasks might have been easier to perform if each target stimulated more than just one vibrating element at a time. Simulations such as the one reported could be valuable in determining the effects of introducing multiple targets and varying range and beamwidth.

In summary, it appears that a tactile imaging system with a range-azimuth display should provide adequate information to the user for locomotor control purposes, although ability to distinguish between different objects is unknown at present. At least the user's auditory sense would be completely unhindered, thus easing the problem of interpreting the many natural sound cues present in the environment.

Finally the mobility aid simulation techniques described previously have been shown to possess sufficient flexibility to be adaptable to tactile as well as auditory displays.

8.3 EFFECTS OF DISPLAY SOUND EXTERNALIZATION

8.3:1 Introduction

In designing the Canterbury Single Object Sensor (S.O.S.) a serious but unsuccessful attempt was made to determine the transfer function of the pirral so that this could be incorporated in the device, helping to "externalize" the display. As a collaborative venture with S.T. Bui, the builder of the Single Object Sensor, an experiment was carried out using the simulation system to investigate the consequences of this failure in terms of locomotor control performance. A brief summary only is given here, solely to illustrate one application of the monitoring and simulation techniques developed in this thesis. More detail can be found in Bui (11).

The term "externalization" refers to the perception of a sound source "outside the head" rather than "inside the head" as is thought to be normal under dichotic listening conditions (using headphones). The causes of the differences between the two types of perception, termed localization and lateralization (12) are still not satisfactorily resolved. A considerable literature exists on localization and lateralization phenomena (12 - 20) and a comprehensive review is not attempted here.

The issue in the present experiment was whether the compromise effected in the design of the S.O.S., whereby I.A.D. only was used as a direction cue, seriously affected locomotor performance. While it was thought desirable that displayed signals appear to come from the objects giving rise to the signals, it might be argued that in terms

of detecting and correcting errors of locomotor control, the magnitude of the cue might be more important than any subjective differences between dichotic and free-field listening conditions.

An experiment was designed to test for differences in locomotor control performance arising from dichotic and free field stimuli. Excepting research by Held (20) and others on auditory reorientation, most previous experiments in localization and lateralization have concentrated on static situations with head movement as the only dynamic feature, and the present study would not have been feasible without the simulation and evaluation system described in previous chapters.

8.3:2 Method

The locomotor control task used in this study was that of approaching a target from a distance of 10 metres. Some data had already been gathered from subjects performing the task under visual conditions and under natural auditory control using a metronome as a sound source (table 4.3).

Since detection of targets beyond 4m was unreliable using the S.O.S., and because some control over display characteristics was desired, the simulation feature of the instrumentation system was used to generate the display of the S.O.S. (See chapter 6).

In the free-field condition, the binaural signals were summed, amplified, and led to a loudspeaker mounted at head height on the target pole.

Five subjects were used in the initial investigations. Each was allowed two practice trials before having his performance recorded for six trials. Four conditions were tested, in a different order for each subject. In the dichotic situation,

normal and doubled I.A.D. conditions were tested, while in the free field situation the test was performed both with the simulated device sound and with a constant, continuous sound (30 Hz square wave), presented via the loudspeaker.

One subject was tested over a longer period, and the last ten of twenty subsequent trials were recorded. Two extra conditions were added to the dichotic stimulus tests - zero I.A.D. and quadrupled I.A.D.

8.3:3 Results

Table 8.2 presents the mean values of RMSDSL, the principal figure of interest, for the five subjects tested in four conditions. It is seen that performance using the dichotic stimuli of the simulated device was inferior to that obtained under free field conditions with the simulated display sound presented via a loudspeaker on the target ($P < .05$, twin-tailed "t" test)

This suggested that an improvement, at least in initial learning rate, would be effected if the display sounds of the present device could be "externalized" properly. It is interesting to note that even for the inexperienced subjects used here, performance in the free-field condition appeared to be degraded if the pitch cue and the loudness shaping within the simulated beamwidth was removed - leaving merely a continuous signal analogous to the metronome condition tested in a previous study (chapter 4). However, performance in this "free field constant signal" condition was still superior to that using the simulated device.

TABLE 8.2

Target Approach Task: Performance under Dichotic and Free Field Conditions.

(Means over 5 Subjects)

<i>RMSDSL (cm)</i>	<i>Dichotic</i>		<i>Free-Field</i>	
	<i>Normal IAD (.5dB/deg)</i>	<i>Doubled IAD (2.0dB/deg)</i>	<i>Display Signal</i>	<i>Constant Signal</i>
<i>Mean</i>	11.2 *	8.1	6.9 *	8.6
<i>Std.Dev.</i>	(2.5)	(2.4)	(1.7)	(4.8)

*Indicates significant difference ($P < .05$ "t" test).

Results for the subject who was given longer training are presented in table 8.3 and bear out the above conclusions. In addition, an improvement in performance occurred under the dichotic stimulus condition as I.A.D. was increased from its normal value (0.5 dB/degree) to 2.0 dB/degree ($P < .05$, twin-tailed "t" test).

Performance in the latter condition was comparable to that obtained in the "externalized S.O.S." condition.

TABLE 8.3

Target Approach Task: Dichotic versus Free Field Conditions.

(Practised Subject).

<i>RMSDSL (cm)</i>	<i>Dichotic</i>				<i>Free Field</i>	
	<i>Zero IAD 0.0dB/deg</i>	<i>Normal IAD .5dB/deg</i>	<i>Double IAD 1.0dB/deg</i>	<i>Quadrupled IAD 2.0dB/deg</i>	<i>Display Signal</i>	<i>Constant Signal</i>
<i>Mean</i>	12.9	9.5 *	7.5	6.0 *	6.5	8.6
<i>Std.Dev.</i>	(5.3)	(3.7)	(2.5)	(2.5)	(2.2)	(4.4)

* Indicates significant difference ($P < .05$ "t" test).

8.3:4 Supplementary Results

Table 8.4 presents results in the pole approach task from an experienced sonicguide user approaching a pole from a distance of 4m - first using his aid, and secondly using a 1.5Hz metronome as a target. Thus no direct comparison of RMSDSL values can be made with the results of previous sections owing to the large difference intravel path length.

TABLE 8.4

Target Approach Task: 4m Approach Distance.

<i>RMSDSL</i>	<i>Sonicguide</i>	<i>Free Field (Metronome)</i>
<i>Mean</i>	3.9	3.6
<i>Std. Dev.</i>	1.8	1.5

Results over six trials from the two conditions tested here were almost identical, no statistically significant difference being present. Although further study and possibly more accurate measurement are needed before any firm conclusion could be drawn from this type of test, it appeared that the subject's long experience with the device had enabled him to use it to orient and travel towards an object within range with a level of skill similar to that exhibited when the object itself was emitting a sound.

8.3:5 Conclusions

The experimental results suggested that subjects would learn to use the Single Object Sensor more quickly and accurately if the display sounds appeared to originate from the objects being sensed. However much less advantage, if any would be gained if each target appeared to emit only a signal constant in pitch and amplitude. Performance of existing devices (the Sonicguide and S.O.S.) may already be nearly equivalent to this latter condition, at least when only a single target is involved. However, some dependence of performance might be expected on the exact nature of the sound emitted by the target.

Further study is needed to establish whether the difference in performance between the dichotic and free field display presentations persists after prolonged aid use.

Finally, the results from one subject suggested that increasing the I.A.D. are in a dichotically presented display can improve performance in the target-approach task. This effect would be consistent with the results of chapter 6, and may be due to increased sensitivity of the subject, regarded as a control system, to any error between his actual and his desired course.

8.4 A COMPARISON OF TWO EXISTING DEVICES

8.4:1 Introduction

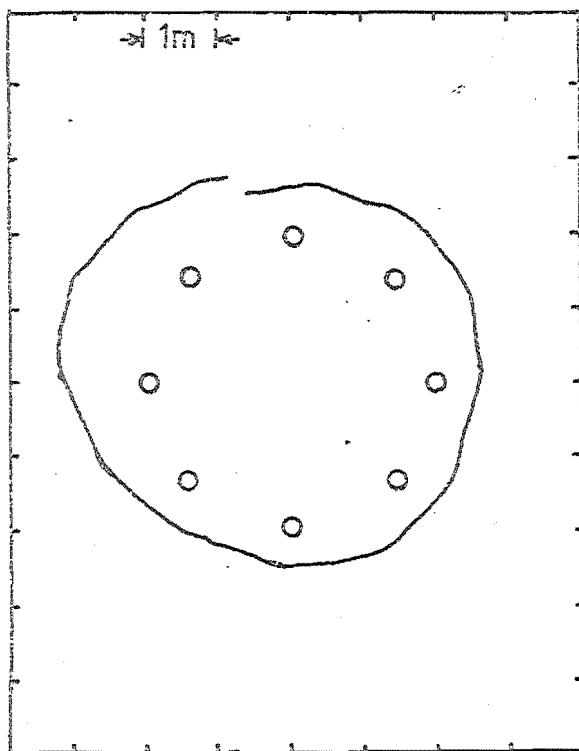
It would be very desirable to test a variety of mobility aid using the techniques outlined in this thesis. Unfortunately only a limited range of experimental aids apart from the Sonicguide was available at Canterbury at the time of writing.

ASide from variations on the "Sonic Glasses" these (such as the children's aid (21) and the monaural vision of the glasses) the other device readily available was the Single Object Sensor (22) developed by Bui and described in Chapter 5 above.

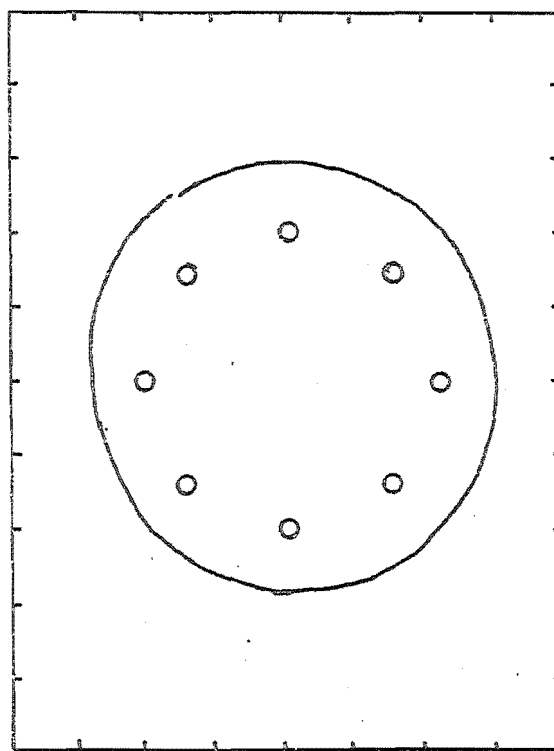
These devices are discussed separately below in terms of their ability to allow accurate locomotor control, and the final section (8.8:4) makes a comparison between them.

8.4:2 The Sonicguide

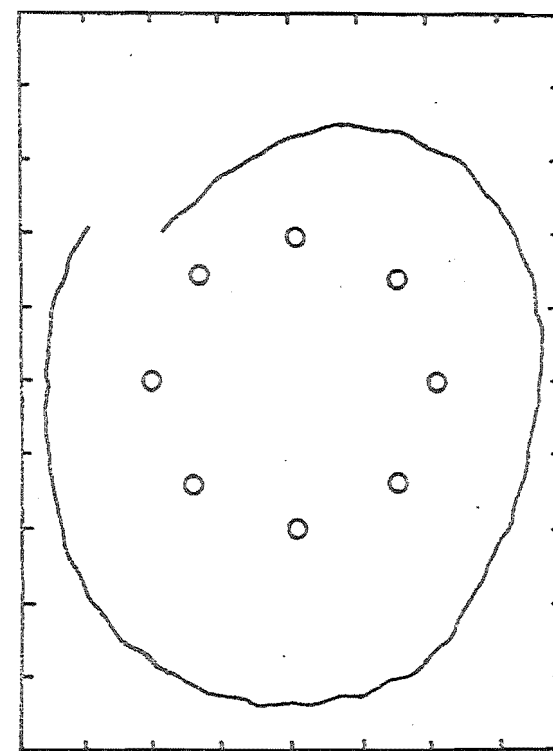
Data from sonicguide users performing controlled environment tasks has already been presented in chapters 4 to 7. A detailed analysis of the locomotor control performance of a skilled, long-term user appears in Brabyn and Strelow (23). In addition to examining performance in the straight shoreline task, this analysis tested the user in slaloming between a row of poles and in following a curved (circular) shoreline. These two tasks require a high degree of control over bodily motion to accomplish at all. The typical path plots of Figures 8.7 (a) and 8.8 (a) show that the subject was able to perform them smoothly and completely, although not so well as a typical sighted subject (Figure 8.7 (b) and 8.8 (b)). For comparison, Figure 8.7 (c) shows a typical plot for a subject attempting to perform the circular shorelining task under blindfold with no artificial spatial information, while Figure 8.8 (c) shows an attempt under similar conditions to perform the slaloming task. Thus an aid such as the sonic guide is definitely capable of use as a primary source of spatial information for locomotor control in relatively difficult tasks.



(a)

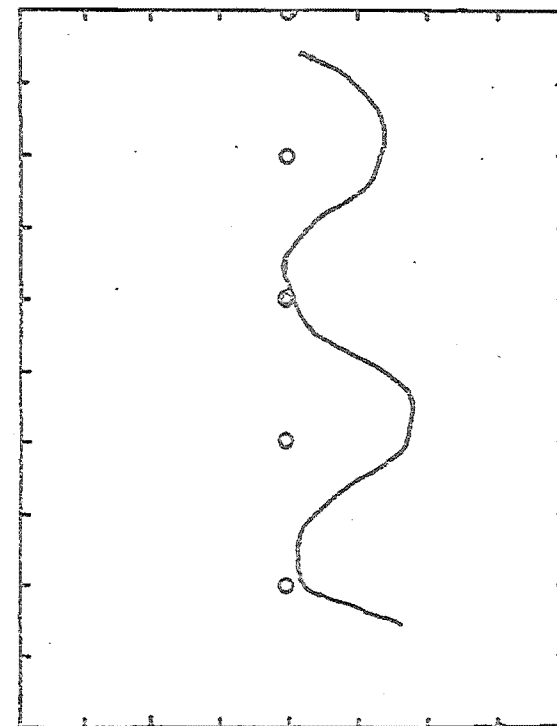
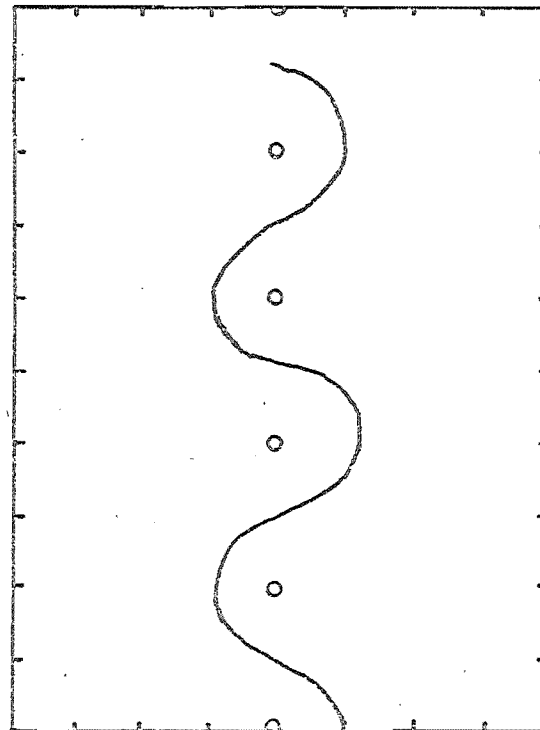
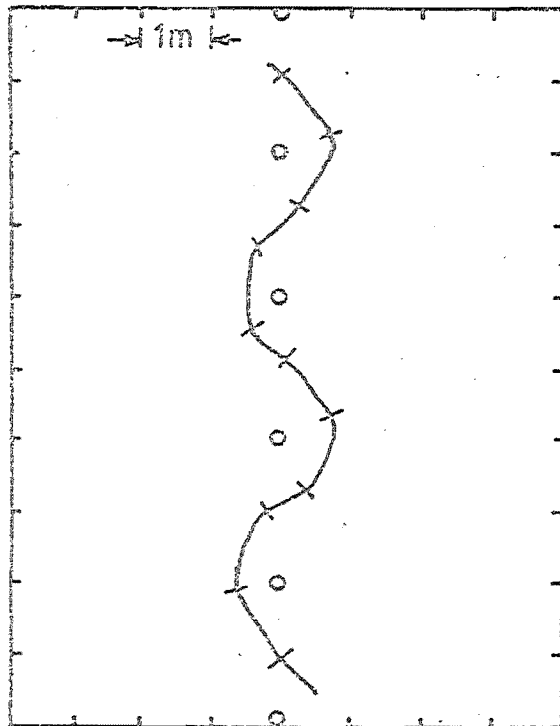


(b)



(c)

Fig. 8.7
"Circle Shorelining Performance"



(a) Experienced Sonicguide User, (b) Sighted Subject,

(c) No Spatial Information.

Fig. 8.8

"Slaloming Performance".

Shorelining data from subjects using the sonicguide is summarised in table 8.5, from which it is clear that even after a brief practice period, RMSDSL values of 12 cm are attainable, while performance after sustained use approaches much closer to the sighted level, although, still more easily discriminated from the latter.

TABLE 8.5

Sonicguide Shorelining Performance

Condition Performance Index	Inexperienced (2 hrs) Subject (Mean of 6 trials)	Experienced (6 yrs) Subject (Mean of 10 trials)
AVSP	92.3 (2.8) *	143.7 (9.4)
RMSDIP	33.8 (22.6)	16.8 (7.0)
RMSDSL	12.9 (5.2)	7.7 (2.5)
SCURV	.672 (.080)	.192 (.022)

* Std. Dev.

8.4:3 The Single Object Sensor

Performance data from the device in the shorelining task for an unpractised subject using the "pack-frame" position sensing linkage (see chapter 4) appears in Kay, Bui, Brabyn, and Strelow (22), indicating a comparable level of performance to that attained by unpractised sonicguide users. Table 8.6 summarises measured shorelining performance levels for practised and unpractised subjects. It is seen that the performance of the experienced subject (averaged over 10 trials after a long practise period) approximates that of the experienced sonicguide user, with a mean value for RMSDSL of 7.3 cm.

TABLE 8.6

S.O.S. Shorelining Performance

<div>Condition</div> <div>Performance Index.</div>	Unpractised (2hrs) Subject (Mean of 6 trials)	Practised (40 hrs) Subject (Mean of 10 trials)
AUSP	103.6 (17.5)	104.1 (2.9)
RMSDIR	28.4 (14.4)	18.1 (13.3)
RMSDSL	14.2 (3.8)	7.3 (3.0)
SCURV	.590 (.169)	.295 (.030)

The fact that these performance levels are so similar presumably reflects the basic similarity of the spatial cues provided by the two devices. Both use I.A.D. (0.3-0.5dB/degree) as the main direction cue, and frequency changes as the range cue. While the range cue of the S.O.S. is approximately

$$\text{P.R.F.} = \frac{177}{R} \text{ Hz}$$

that of the sonicguide is (neglecting Doppler effects) approximately

$$f = 850 R$$

The investigations of chapter 6 showed that reduction of the rate of change of pitch with range produced noticeable effects if the reduction was as great as 10 to 1. In the present case, the effective reduction is approximately 5 to 1, and this should have only marginal effects on locomotor control performance.

The remaining principal difference in spatial information provided by the two displays is the fact that only the nearest object within the beam is displayed by the S.O.S., while any number of objects may appear in the sonicguide display. However the findings of chapter 5 suggest that this difference has little effect in the shorelining task used here. This conclusion is supported by subjective assessment which suggests that the closest pole in the shoreline tends to be dominant in the display. For example, objects at greater distances produce considerably quieter signals than closer ones.

In sum, the similarity of performance levels achieved by users of these two devices in the shorelining task is not surprising in view of previous results obtained using the simulation system.

It was interesting to observe the performance of an experienced sonicguide user with the S.O.S. After practising for approximately 20 trials, he was able to achieve values of RMSDSL even better than those achieved by the experienced S.O.S. user, although he showed a tendency to remain very close to the shoreline, increasing the RMSDLP measure. This effect was probably due to the fact that the beamwidth of the S.O.S. (approximately 50°) is somewhat narrower than that of the sonicguide, causing the subject to remain closer to the shoreline in order to keep the poles within the device's beam.

The experienced S.O.S. user was also tested in the circle and slalom tasks, and while performance was satisfactory (Figure 8.9) it did not appear to reach the level of competence achieved by the sonicguide user.

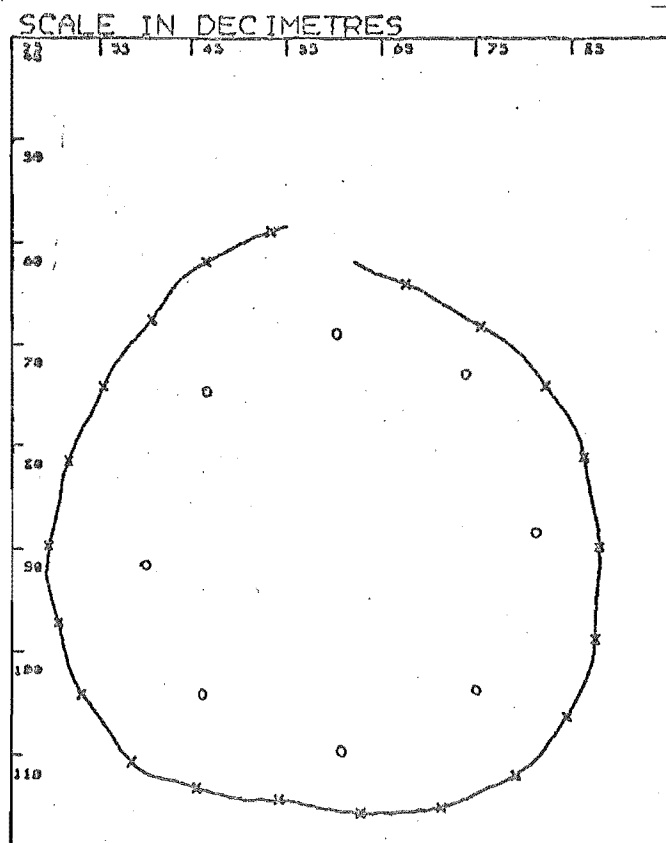


Fig. 8.9

"Circle Shoreline Task: Experienced S.O.S. User"

8.4:4 Summary

In comparing the Sonicguide and the S.O.S., it appears that in terms of the level of locomotor control achieved in controlled environment tasks, both are equally good. It must however be realized that other factors come into an overall evaluation. Although these factors largely fall outside the main considerations of this thesis, some mention is made of them here.

Perhaps the most striking difference between the two displays is that unlike the sonicguide, the S.O.S. allows very little discrimination between different types of targets, and therefore cannot be as helpful in recognizing landmarks as the former device. Reference to this feature is made in Chapter 9.

Another difference which arose in studying the S.O.S. was its reduced reliability in detecting some targets. A series of six trials performed by the experienced subject, shorelining the wooden poles used in previous experiments with the sonicguide, yielded an average RMSDSL value of 12.4 cm. This compares unfavourably with the figure of 7.3 cm in Table 8.6, obtained using larger aluminium poles which gave more reliable signals.

8.5 OTHER APPLICATIONS

8.5:1 Gait Analysis

The monitoring system and associated performance measures may be useful in gait analysis as opposed to "locomotor control". In this respect, the speed-derived measures "surplus curvature", and the graph of speed-versus time are helpful.

In analyzing the locomotor control performance of a long-term sonicguide user (23), it was noticed that, apart from a lessened ability to accurately control his bodily path (quantified by RMSDSL

and RMSDIP) , two features differentiated his travel from sighted travel (Table 8.7). Secondly, it was smoother, as shown by the

TABLE 8.7

SHORELINING PERFORMANCE

<i>Condition</i> <i>Index</i>	<i>Sonicguide</i>	<i>Normal Vision</i> <i>6 S's</i>	<i>Sonicguide</i> <i>with Metronome</i>
AVSP	143.7 (9.4)*	122.3 (6.8)**	106.0 (4.9)*
AVAC	25.5 (5.4)	41.8 (15.6)	31.3 (4.6)
RMSDIP	16.8 (7.0)	6.5 (1.8)	16.2 (7.2)
RMSDSL	7.7 (2.5)	3.4 (0.8)	9.9 (4.5)
SCURV	.192(.022)	.328(.151)	.345(.028)

AVSP	=	Average Speed	cm/sec
AVAC	=	Average Acceleration	cm/sec ²
RMSDIP	=	RMS Deviation from Ideal Path	cm
RMSDSL	=	RMS Deviation from Straight Line	cm
SCURV	=	Surplus Curvature	rad/m
*		within <u>S</u> standard deviations	
**		between <u>S</u> standard deviations	

low AVAC values. This smoothness was also reflected in the low SCURV value, since SCURV is particularly sensitive to small path fluctuations. Figure 8.10 shows typical speed plots for the aid user and a sighted subject in the shoreline task. The blind subject

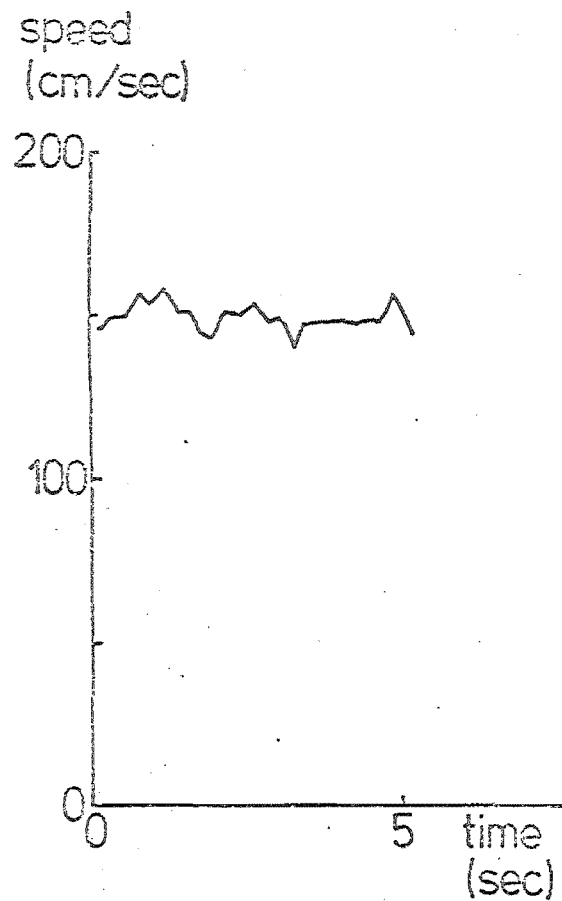
shows a comparative absence of speed variations compared to the sighted subject, whose every step can be seen in the speed plot. That this smoothness was observed for fast travel was particularly notable as the speed deviations have been generally observed to become more pronounced at high speeds.

These data assisted in understanding why this aid user's travel appeared unusual even to visual inspection. With the help of the performance measures it became clear that the fault being observed was an unnatural smoothness of travel, that even his fastest walking was done with a smooth, "gliding" motion.

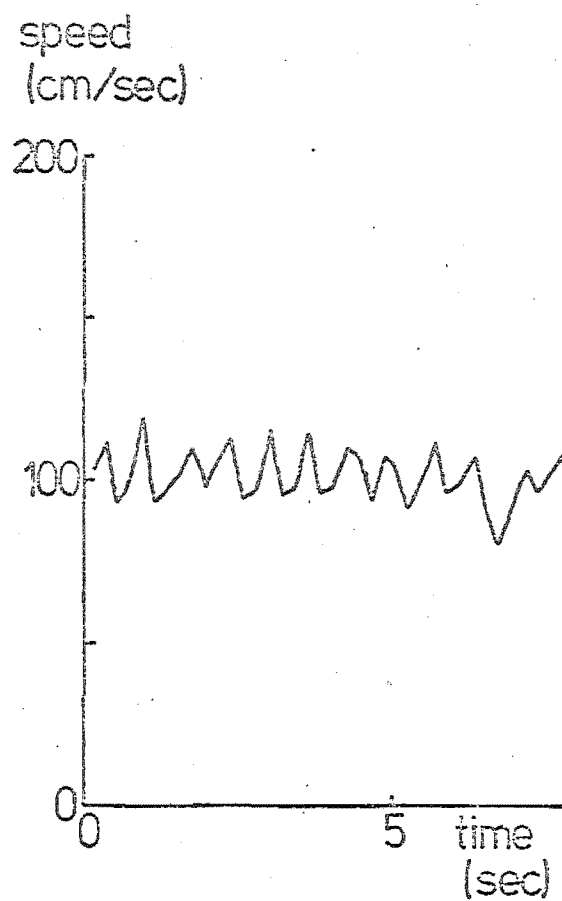
In an attempt to make this subject step in a more natural manner, he was asked to pace himself in time to a metronome set at 1.5 Hz, a walking rate found to be typical of sighted travel. It was expected that this would make his gait more deliberate.

A typical speed plot for this condition is shown in Figure 8.11c, where it is evident that the subject was walking more slowly and the speed was changing more noticeably with each step. From table 8.7, it can be seen that his speed (AUSP), acceleration (AVAC) and path curvature (SCURV) measures were closer to sighted values. The two path deviation measures showed only small changes. Most importantly, visual assessment now was that he looked more like a sighted traveller.

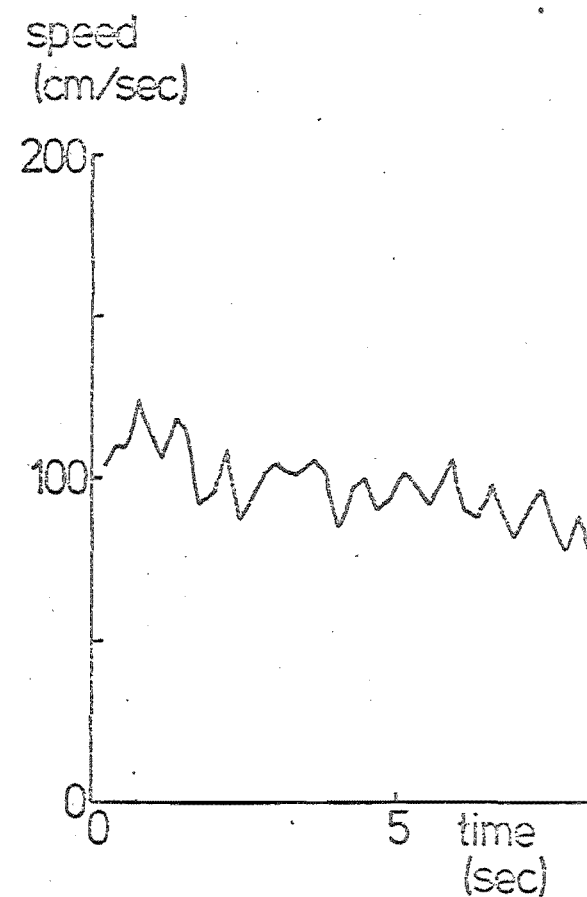
It would therefore appear that travel which has the appearance of sighted mobility is not necessarily the smoothest possible, but includes a moderate amount of body jerk and sway.



(a) Sonicguide User



(b) Sighted Subject



(c) Sonicguide User and Metronome.

Figure 8.9 Typical Speed Plots.

Plots of speed versus time for various parts of the body are already obtainable from other types of instrumentation such as the tachistograph (24). Most research on the subject of human gait has been in connection with limb prosthetics and physiotherapy (25). The present instrumentation system could have applications in this area, particularly since motion is not restricted to one dimension as in the tachistograph, and therefore lateral as well as forward perturbations in movement caused by prosthetic limbs could be examined. In order to optimise the system for this purpose, some changes would be desirable, such as lowering of drum inertia and shortening of the sensing lines to further improve accuracy and time response - the latter feature being particularly important in gait analysis.

8.5:2 Effects of Drugs on Walking Performance

An application of the locomotor control measurement techniques which has already been exploited in conjunction with the Psychology Department of the University of Canterbury is the measurement of acute effects of alcohol on walking performance. The target approach task was used for this study, the results of which are reported in Gregson, Smith, Strelow, and Brabyn (26). Previous researchers in this type of socially important area have been, in the main, confined to the use of wooden beams (27), balance platforms (28), or simple mechanical systems (29), and the present system was regarded as a considerable advance in accuracy and sophistication.

The system was able easily to distinguish performance of subjects who had been given a "dose" (1 gm/kg body weight of pure alcohol from

those given a 'placebo' (0.1gm/kg body weight). Performance variations were monitored over 80 minutes after the alcohol was administered, and in addition to the normal pole approach task a "complete walk" was used in which subjects were asked to approach the target with arms crossed and walking heel to toe in time with a 1.5 Hz metronome. This allowed discrimination between performance changes in familiar and unfamiliar tasks. Attention was not restricted to locomotor control accuracy, significant effects being discovered in gait (speed-derived) measures as well as in path deviations.

Effects of drugs other than alcohol could be investigated using the techniques of this study, and the method could be a useful adjunct to blood sampling and other procedures used to estimate a person's ability and safety in sensory-motor tasks.

REFERENCES

- (1) Collins, C.C.; Modey, J.M.J.; "Tactile Sensory Replacement". Proc. San Diego Biomedical Symposium, 1974, Vol. 13.
- (2) Collins, C.C.; "Tactile Television: Mechanical and Electrical Image Projection". IEEE Trans MMS, 1970, MMS - 11, 65 - 71.
- (3) Bach-y-Rita, P., Collins, C.C., Saunders, F., White, B., Scadden, L.; "Vision Substitution by Tactile Image Projection". Nature, 1969, 221, 963 - 4.
- (4) Collins, C.C.; Scadden, L.A., Alden, A.B.; "Mobility Studies with a Tactile Imaging Device". Conf. on Systems and Devices for the Disabled, Seattle, June, 1977.
- (5) Bliss, J.C.; "A Relatively High Resolution Reading Aid for the Blind". IEEE Trans MMS, 1969, MMS - 10, 1 - 9.
- (6) Bliss, J.C.; Katcher, M.H., Rogers, C.H., Shepard, R.P.; "Optical-to-Tactile Image Conversion for the Blind". IEEE Trans MMS, 1970, MMS - 11, 58 - 65.
- (7) Gardiner, K.W., Bliss, J.C.; "An Optical to Tactile Image Converter". In R. Dufton (Ed.) Proc. Int. Conf. on Sensory Devices for the Blind. London: St. Dunstan's, 1967 299 - 308
- (8) Starkiewicz, W., Kuleszewski, T.; "Progress Report on the Electroftalm Mobility Aid". Proc. Rotterdam Mobility Research Conference. New York: American Foundation for the Blind, 1965 pp 27 - 38.
- (9) Gibson, J.J.; "Visually Controlled Locomotion and Visual Orientation in Animals". Brit. J. Psychol, 1958, 49, 182 - 194.
- (10) Johnston, I.R., White, G.R., Summing, R.W.; "The Role of Optical Expansion Patterns in Locomotor Control". Am. J. Psychol, 1973, 86, 311 - 324.
- (11) Bui, S.T. Unpublished Ph. D. Thesis.
- (12) Mills, A.W.; "Auditory Localization". In Foundation of Modern Auditory Theory, J.V. Tobias (Ed.) Academic Press 1972, pp 303 - 348.

- (13) Stevens, S.S., Newman, E.B.; "The Localization of Actual Sources of Sound" Am.J.Psychol, 1936, 297 - 306.
- (14) Jeffres, L.A., Taylor, R.W.; "Lateralization VS Localization." J. Acoust. Soc. Am., 1961, 33, 482 - 483.
- (15) Plenge, G.; "On the Differences Between Localization and Lateralization". J. Acoust. Soc. Am, 1974, 56, 944 - 951.
- (16) Moushegian, G., Rupert, A.L.; "Relations Between the Psychophysics and the Neurophysiology of Sound Localization". Federation of America, Soc. of Exp. Biol. Proc., 1974, 33, 1924 - 7.
- (17) Wallach, H., Newman, E.B., Rosenzweig, M.R.; "The Precedence Effect in Sound Localization", Am. J. Psychol, 1949, 62, 315 - 36..
- (18) Batteau, D.W.; "The Role of the Pinna in Human Localization". Proc. Royal Society, 1967, 168, 158 - 180.
- (19) Fisher, H.B., Freedman, S.J.; "The Role of the Pinna in Auditory Localization". Journal of Auditory Research, 1968, 8, 15 - 26.
- (20) Held, R.; "Shifts in Binaural Localization after Prolonged Exposures to Atypical Combinations of Stimuli" Am J. Psychol. 1955, 68, 526 - 48.
- (21) Kay, L.; "The Binaural Sensory Aid: Sensory Parameters for use by Blind Babies". In Preparation.
- (22) Kay, L., Bui, S.T., Brabyn, J.A., Strelow, E.R.; "Single Object Sensor: A Simplified Binaural Mobility Aid". Journal of Visual Impairment and Blindness, May 1977.
- (23) Brabyn, J.A., Strelow, E.R.; "Laboratory Studies of Locomotor Performance and Gait Characteristics of a Skilled Sonicguide User". In preparation.
- (24) Contini, R., Gage, H., Drills, R.; "Human Gait Characteristics" Biomechanics and Related Topics - Proceedings of a Symposium held in Glasgow, September, 1965. R.M.Kenedi, Ed. Pergamon Press, Oxford, 1965.
- (25) Cheng, I., Koozekanani, S.H., Fatehi; "A Simple Computer Television System for Gait Analysis". IEEE Trans on Biomedical Engineering, 1975, BME - 22, pp 259 - 260.
- (26) Gregson, R.A.M., Smith, D.A.R., Strelow, E.R., Brabyn, J.A.; "Acute Effects of Alcohol on Measures of Walking Performance". Applied Psychological Measurement (In Press).

- (27) Fregly, A.R.; "Relationship between Blood Alcohol, Positional Alcohol Nystagmus and Postural Equilibrium". Quarterly J. of Studies on Alcohol, 1967, 28, 11 - 21.
- (28) Begbie, G.H.; "The Effects of Alcohol and of Various Amounts of Visual Information on a Balance Test". Ergonomics, 1966, 9:1, 325 - 333.
- (29) Miles, W.R.; "Static Equilibrium" Methods Med. Res. 1950, 3, 157 - 65.

CHAPTER 9

ADVANCING LOCOMOTOR CONTROL AND MOBILITY THEORY9.1 INTRODUCTION

Evidence from the preceding experiments has shown that subtle distinctions can be made between levels of locomotor control performance attained in "controlled - environment" tasks under different conditions of sensory input. It still remains, however, to make use of this accumulated body of knowledge in gaining a deeper understanding of the mobile human, and to clarify the relationship between locomotor control skill and the more all-encompassing skills of mobility-navigation over long distances in the outdoor environment.

In the present chapter, a simple model of the mobile human as a control system is proposed, and some deductions are made regarding the best form of man-machine interface suitable for locomotor control. Finally an attempt is made to evaluate the relevance of laboratory studies in the overall context of mobility.

9.2 A CONTROL SYSTEM MODEL OF PURPOSEFUL LOCOMOTION9.2:1 Introduction

It was stated in chapter 2, quoting from Kay (1) that the human control system in mobility is too complex to model at present. However, the studies of locomotor control reported in previous chapters have given sufficient insight into the problem for a simple model to be proposed. It should be stressed that such a model is only intended to apply in describing a subset of overall

mobility skills - that of locomotor control, the control of bodily path through, and with respect to the immediate environment.

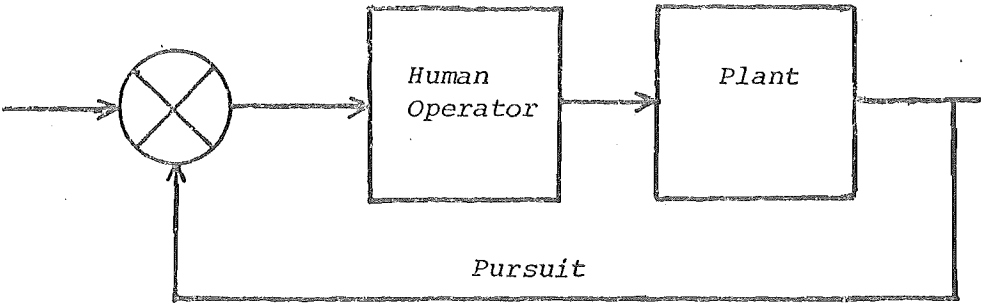
9.2:2 The Human Operator in a Control Loop

The development of Systems Identification Techniques over the last 30 years has enabled the characteristics of human operators in control loops (aircraft, motor vehicles, etc.) to be modelled with some limited success. The human operator's task in most cases is to reduce the error between the actual system output and the desired output to zero.

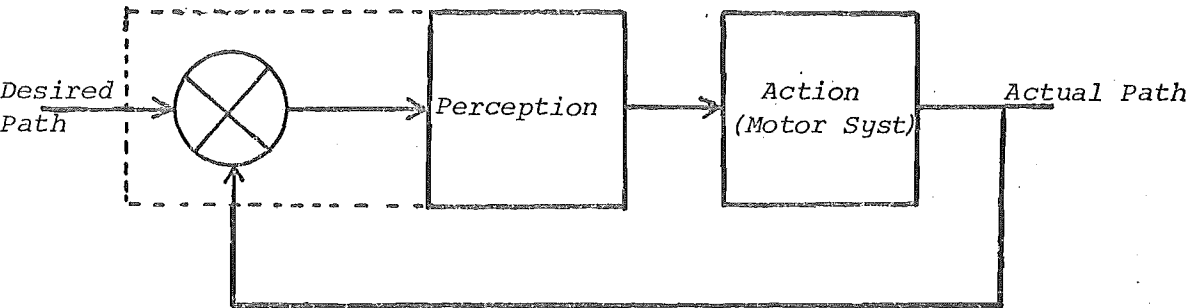
Figure 9.1 gives a representation of a human "operator" in the mobility situation. His path through the environment is regarded as the controlled variable. Acting upon whatever spatial information he is given, it is assumed that he forms an estimate of his error from the desired path, and takes appropriate corrective action. In this case the "controller" is the brain and nervous system, while the controlled "plant" is the human body and its motor system.

In previous research on the human operator (2 - 9), the plant dynamics have usually been known, and one of the objects (4) has been to discover the limitations of human operator control so that plants (such as fighter aircraft) can be given characteristics which are optimised for manual control.

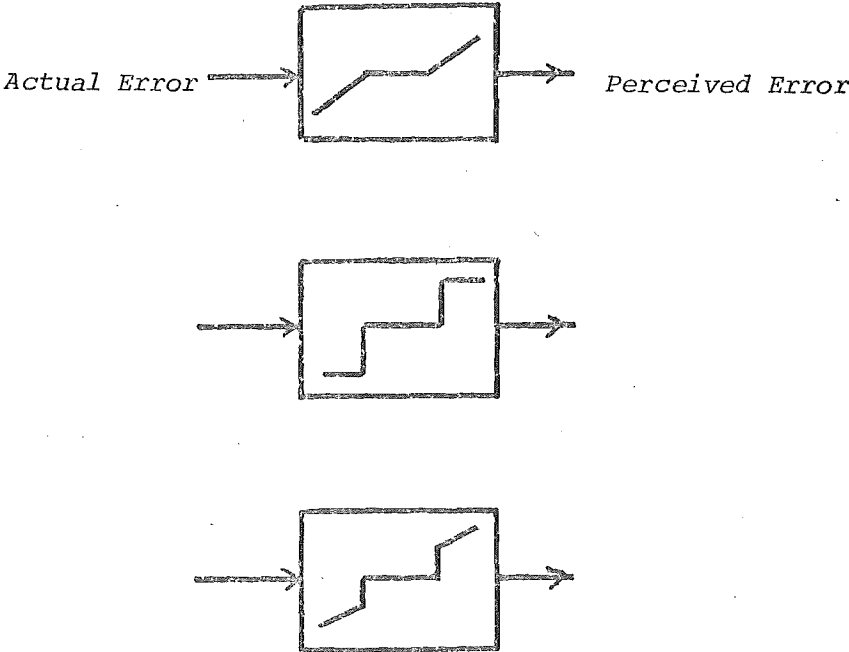
The object in the case of human mobility is to assist in understanding the operation or control strategy of the mobile human - in the hope that enhanced understanding should, in future, lead to improvements in display characteristics.



(a) Human Operator in a Control Loop.



(b) Human Operator in Mobility.



(c) Possible Error Perception Threshold Functions.

Fig. 9.1
"The Human Operator".

9.2:3 Linear and Non-Linear Models

Because linear system theory has been so well developed it has dominated attempts to model the human operator. Bode, impulse, and step response techniques are restricted to linear systems. Similarly cross-correlation methods apply only to linear models, although a development of these has been established in which non-linear systems can be modelled using a linear approximation, or "describing function" (2,6). Apart from the assumptions made covering the operator and plant characteristics in this method of analysis, it is a necessary condition that all signals in the system, including its input, are Gaussian processes. These assumptions are not convenient or realistic in mobility.

All the studies of linear models have used situations where linear behaviour might be expected - error is displayed on an analog display such as an oscilloscope, and control action is exerted via a proportional control such as a joy-stick. Hall (7) showed that under these conditions non-linear behaviour is most evident when signals are changing slowly.

It was shown in 1953 by Bushaw (8) that the control policy of a linear servomechanism was inferior (in terms of time taken to reduce an error signal to zero) to some non-linear systems such as the bang-bang controller. If the human is regarded as a control system, there is no reason for assuming that linear control policies will generally be adopted. On the contrary, evidence has been obtained (9, 10, 11) which shows that control of limb and eye movements is highly non-linear. Perception itself is a non-linear process, in which thresholds can be important. When cues are weak, as they often are in blind mobility (e.g. auditory echo cues) the effects of threshold of

error detection are likely to be very important, and the perceived tracking error (figure 9.1) will be a non-linear function of the actual error. Possible threshold functions appear in figure 9.1(b).

Observation of a large number of path plots obtained from the computer - lined instrumentation system has supported and illustrated this threshold effect. Figure 9.2 shows typical path plots from subjects asked to approach a sound source under blindfold. The initial course was pursued until the error between it and the desired path became so large as to be noticeable, at which point the subject would alter course, sometimes suddenly. Similar effects were often noted in the shorelining task. Whether or not course changes were sudden, they could be interpreted in terms of a threshold effect. For example, the second threshold characteristic of Figure 9.1 (c) would result in only gradual course change after the threshold was exceeded. This type of characteristic is one possible interpretation of plots such as Figure 9.3.

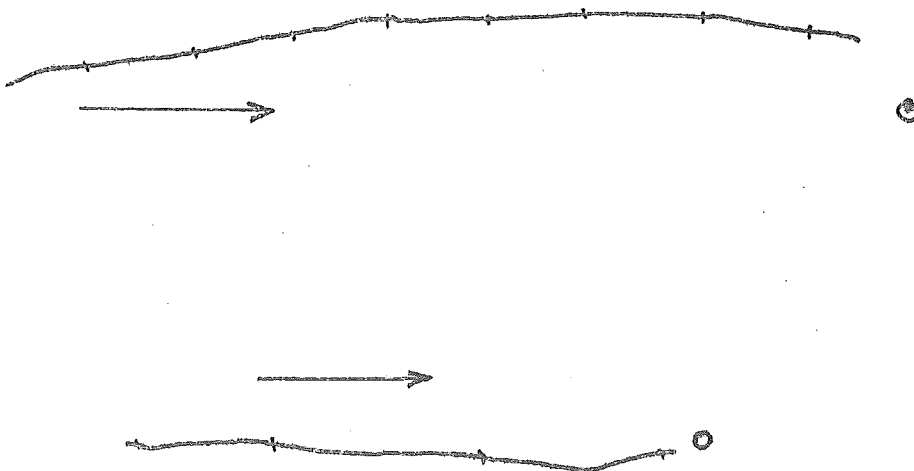


Fig. 9.2

Subjects Approaching Sound Sources

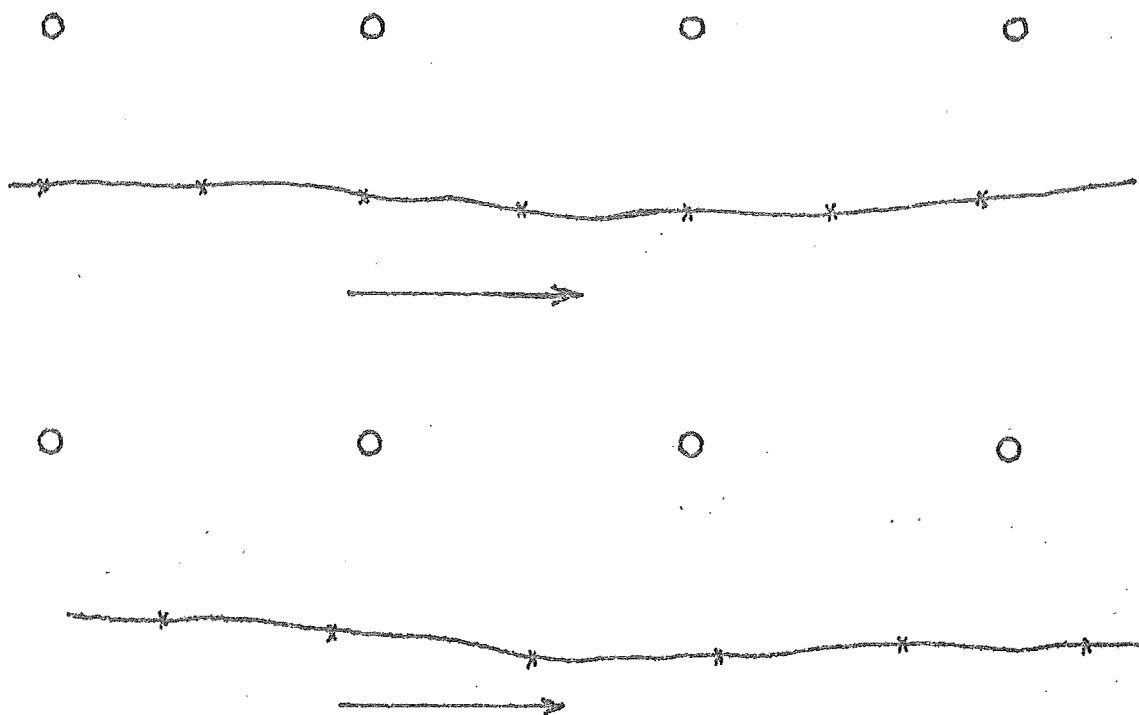


Fig 9.3
Shorelining Plots (Sonicguide User)

Plots from sighted subjects naturally do not show these effects to the same extent since the threshold of error perception in this case is extremely low, even though the same process may be operating.

The above considerations taken together, suggest the use of a non-linear model for the blind human operator in the locomotor-control task. In order to obtain data on such a model, it is necessary to use the "model reference" technique of system identification, which is applicable to both linear and non-linear systems. The technique, illustrated in figure 9.4, is to make some assumption regarding the mathematical form the model should take, and then optimise the model parameters so that model performance agrees as closely as possible with observed performance, according to a least - integral square error criterion.

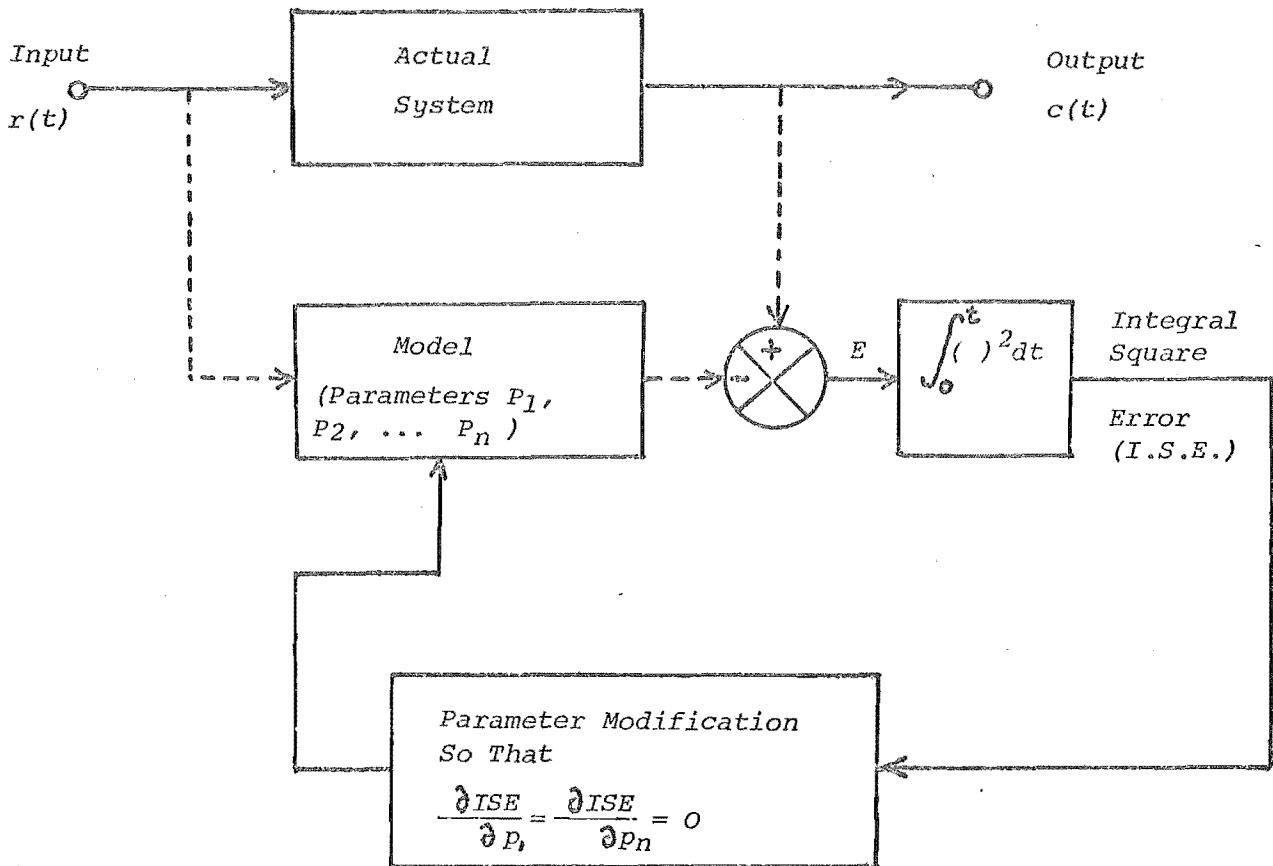


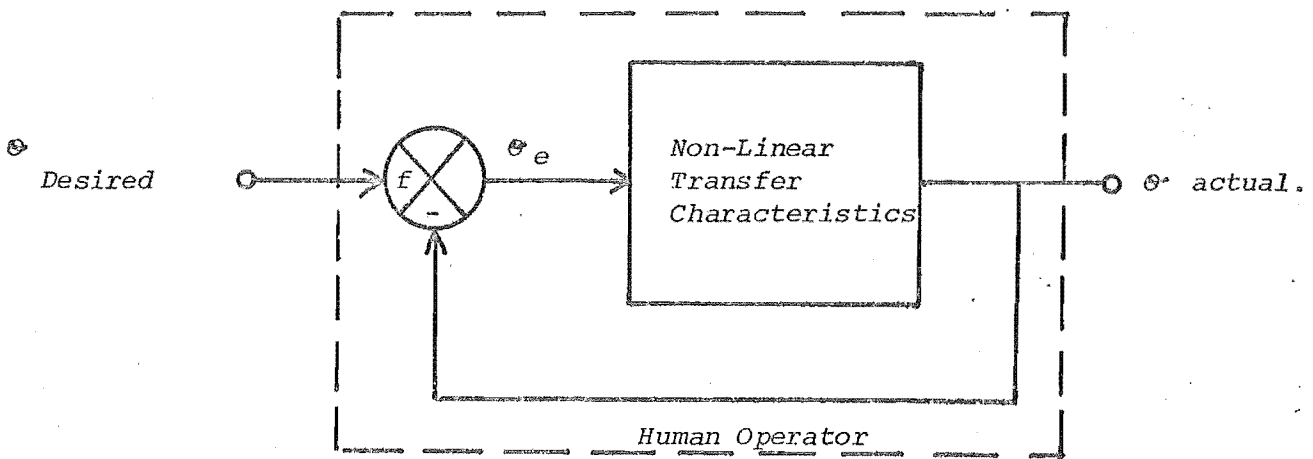
Fig 9.4
"Model Reference" Technique.

9.2:4 Formulation of Model

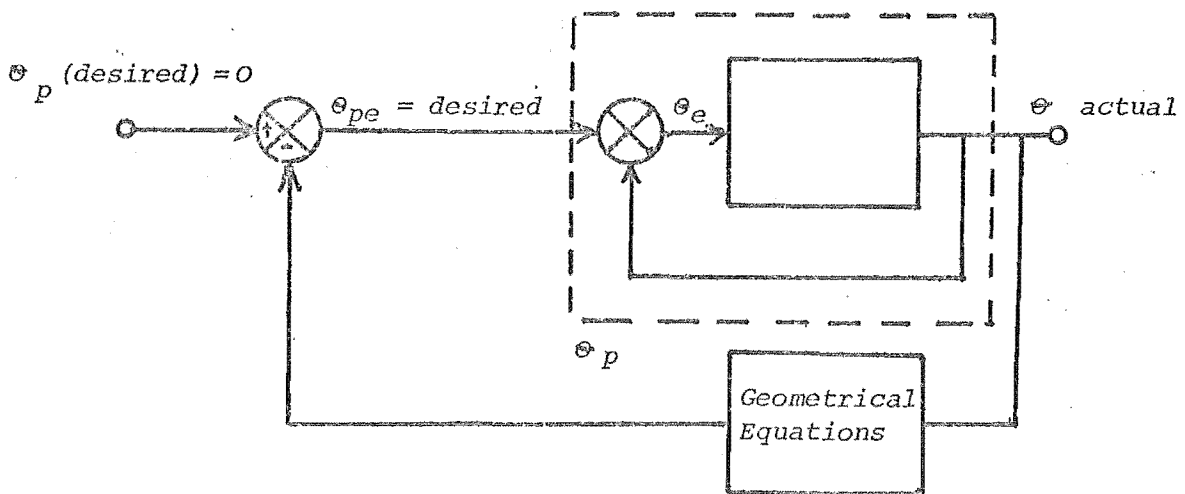
In formulating an initial model, it was assumed that the subject's orientation, or direction of motion, is more important than his speed, since the former dictates any deviations from the specified path. Hence to keep the number of controlled variables down to one, only path direction, θ , is considered in the model. Alternatively, lateral displacement from some specified ideal path could be used as the controlled variable.

It was decided to concentrate initially on a simple task such as approaching a pole from a distance of 10 metres, or approaching a pole so as to pass it at a distance of one metre. In either case, the task is very well-defined, and consists merely of keeping the angle θ subtended from the subject's path direction to his aiming point equal to zero (Figure 9.5). Previous models for the human operator using other tasks

have used all or some of the characteristics of Figure 9.6 (a) - a P.I.D. controller, a pure time delay, and a low-pass filter. In the present setting, as noted above, a threshold characteristic appears to be of major importance, as subjects are observed to drift considerably off the "ideal" path before the error is noticed and a change in course is made.



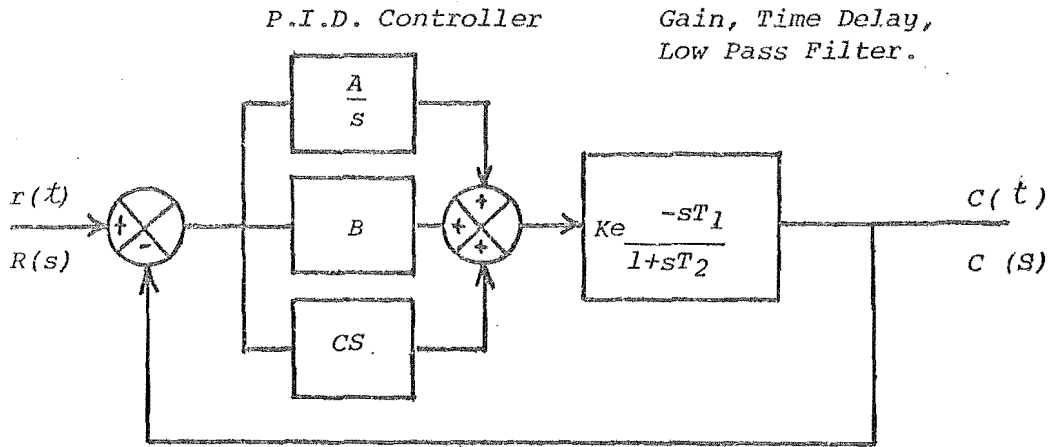
(a) Human Operator Model for a Locomotor Control Task.



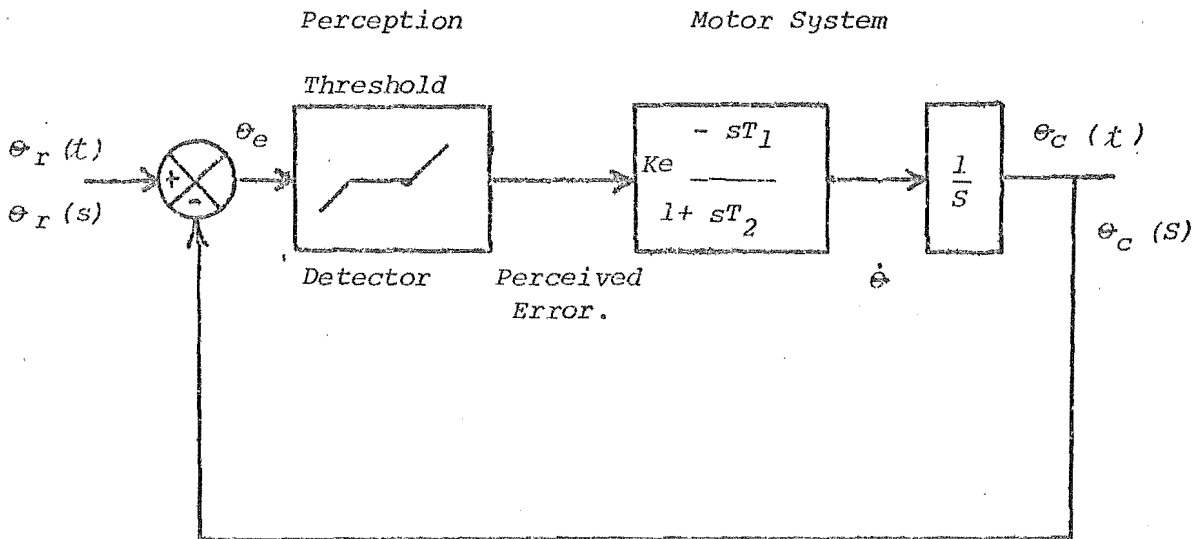
(b) Formulation for Pole Approach Task Allowing Application of Model Reference Technique to Human Operator (shown dotted).

Fig. 9.5
Formulating a Model

The model of Figure 9.6 (b) is therefore proposed. The threshold detector might take the form shown or one of the alternative forms of Figure 9.1.b.



(a) Traditional Model.



(b) A Proposed Model.

Fig. 9.6
Human Operator Models for Locomotor Control

The proposed model has four parameters to be determined - namely:

1. Threshold or dead zone d .
2. Gain K .
3. Time Delay. T_1 .
4. Filter Time Constant T_2 .

These parameters could be obtained by applying the model reference technique described above to the raw position data from the monitoring system. Because of the system's temporal limitations, parameters 3 and 4 are probably not obtainable at this stage, as values of T_1 have been found to vary between 0.1 and 0.2 seconds for human operator models in other applications (6). An attempt could, however, be made to evaluate the parameters of the reduced model formed by setting T_1 and T_2 to zero. It might be expected that values of the dead zone, d , would be reduced as subject experience and skill is increased, or as any steps are taken to enhance incoming cues so that the subject's threshold of perception of error is reduced. For example, if Interaural Amplitude Difference is used as the cue to the relative position of the target in a pole approach task, an increase in I.A.D. should decrease the threshold of error detection. Similarly, values of " d " obtained for sighted subjects in any task should be well below the level for blind subjects.

9.2:5 Implications

Mills (12, 13, 14) has determined the interaural intensity difference which is most noticeable when co-phasic pulses of tone are presented dichotically. This threshold is found to lie between 0.5 and 1 dB, depending upon the tone frequency. Above 1 kHz the value averages approximately 0.6 dB. This implies that changes in I.A.D. of less than

this amount are unlikely to be perceptible, although under dynamic conditions accuracy of perception may change.

The I.A.D. specification for the Sonicguide is 0.3 - 0.5 dB/degree. Even this characteristic is only extant in the central portion of the beam, ambiguities arising at the beam edges (Figure 9.7). Thus the azimuth threshold for this device could be estimated at approximately 2-3 degrees.

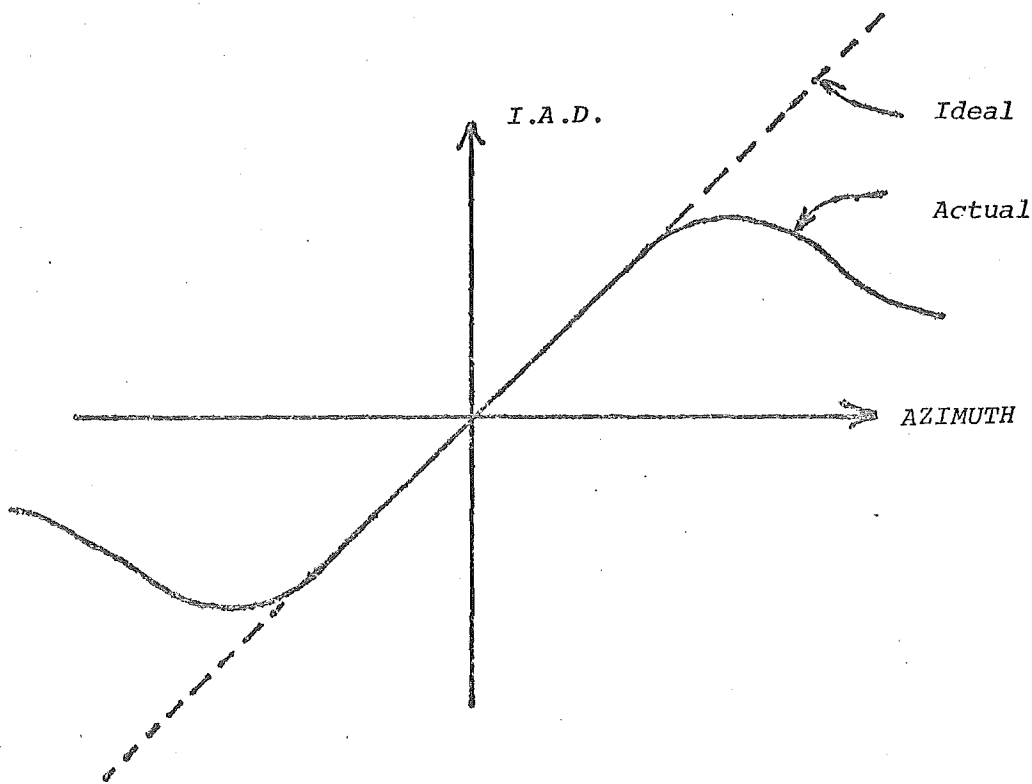


Fig 9.7

Real and Ideal I.A.D. Characteristics.

In the shorelining situation of Figure 9.8, the effect of such a threshold is apparent. Over a 2-metre distance - during which time attention is probably concentrated on a single pole - the subject could find himself ± 10 cm in error from the straight line he is intended to follow. If this were a peak value for his fluctuations from a straight path, the rms value would be approximately 7 cm, corresponding closely

to the actual "RMSDSL" value obtained from an experienced subject.

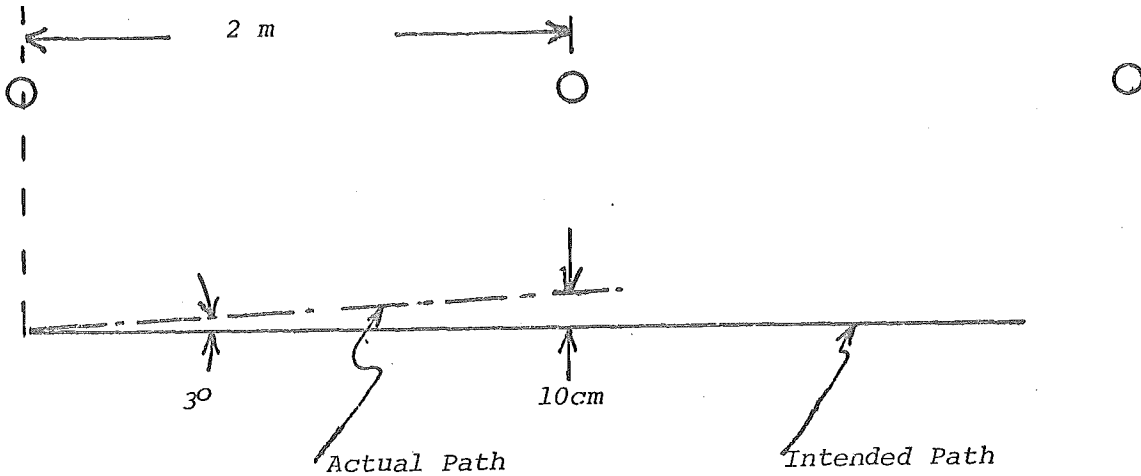


Fig. 9.8
Effect of 3° Error Threshold.

Following this crude analysis, all other things being equal, doubling the I.A.D. should halve the threshold of error, halving the measured path deviations. The "theoretical" and actual effects of changes in I.A.D. on this experienced subject are shown in Figure 9.9.

While these calculations are somewhat over-simplified, the concept of an error threshold does appear to offer one explanation of some experimental results.

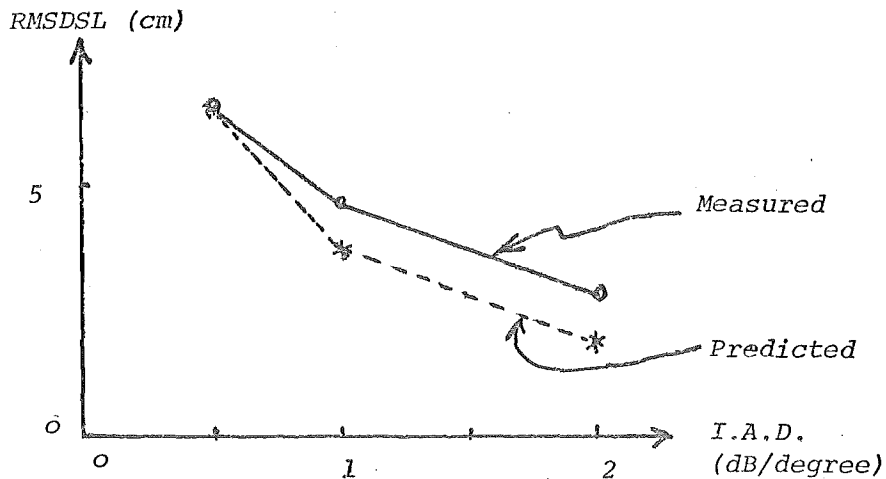


Fig. 9.9
Effects on Experienced Sonicguide User of
I.A.D. Variation.

9.3 LABORATORY STUDIES IN CONTEXT

9.3:1 The Relevance of Locomotor Control Studies.

Much has been said in this thesis concerning "locomotor control tasks" in a "controlled environment". To what extent are these terms meaningful in the wider context of blind mobility, and how beneficial is it to study them?

Sighted people generally walk in straight lines unless they have to avoid obstacles. Maintenance of a reasonably straight course requires some control over bodily path relative to the immediate environment, and the degree of this control possessed by blind and sighted subjects under various conditions of sensory input has been the subject of the objective laboratory studies reported here.

While it might be conceded, then, that some degree of locomotor control is needed in mobility, are the distinctions drawn by laboratory studies between, for example, normally sighted and blind (aided) levels of control so fine as to be inconsequential? Surely a pedestrian never needs to control his bodily path to within a few centimetres or inches? Here again, consideration of everyday mobility suggests otherwise. Even passing through doorways requires bodily control of a high order, while in busy shopping environments frequent, rapid, and accurate course changes are required if collisions with other pedestrians, lamp standards, rubbish tins, and shop windows are to be avoided. An error in judgement of one inch can often mean the difference between bumping or missing a fellow pedestrian. In other words, very accurate control over body movements with respect to objects in the immediate environment is necessary for sighted-like mobility.

The problem is partly obviated for cane users by the fact that other pedestrians show a marked tendency to recognise that the person is blind and clear his path. Whether or not this approach is acceptable

depends upon the extent to which the aim "to enable blind people to travel with the ease, safety, and grace of sighted pedestrians" is taken seriously. If the blind are, eventually, to be indistinguishable and inconspicuous in a crowd of pedestrians, the means must be found for them to develop their locomotor control skills to a high degree.

Once this is agreed, it is clear that any attempt made to assess progress towards this goal of sighted-like locomotor control skills is most easily and objectively performed in a laboratory where the environment is carefully controlled, rather than in the uncontrolled street environment where randomness of traffic, ambient noise, etc., as well as difficulty of instrumentation are all additional problems.

Under laboratory conditions it is possible to measure the variables of interest with high precision, using tasks which are easily understood even by blind-folded subjects. Sensitive experiments, likely to produce conclusions, can therefore be carried out.

In this thesis, locomotor control skill has been assessed using a number of simple tasks which require the subject to control his movements accurately with respect to his immediate environment. It was found that even in the shorelining task, which lends itself to simple quantitative analysis, fine distinctions between levels of locomotor control could be made. This discovery led to adoption of this task as the principal mode of comparison for a large variety of experimental conditions.

9.3:2 Relationship Between Laboratory and Field Studies.

It is difficult to decide where the line should be drawn between laboratory and "real-world" studies of mobility. The laboratory methods outlined in this thesis are by no means intended as a comprehensive solution to the evaluation problem - there is no substitute for field trials. The dichotomy between objectivity and realism is difficult to

resolve. On the one hand, however, some degree of objectivity can be attempted in the real world - the evaluation methods of Armstrong (see chapter 2) being an example - while on the other hand much could be done to make laboratory conditions more realistic. For example, use of an artificial footpath with a wall on one side and a kerb on the other would allow direct comparisons to be drawn with long cane performance.

While it is believed that a great deal of useful, objective, basic information on locomotor control in mobility can be obtained by the methods outlined in this thesis, it may be necessary to use more complex tasks to distinguish some aspects of mobility and performance. For example, while some aids, such as the Single Object Sensor, give only positional information about objects, others, such as the Sonicguide, also give identification information. Detecting any alteration in performance due to this difference may be difficult, and investigation would require either arrangements of different objects in a laboratory, or observation in an outside environment.

This conceptual leap leads slightly beyond the realm of locomotor control, into the more complex global mobility problem of landmark recognition and navigation. Clearly, extending objectivity further into this area is the next step. It is to be hoped that the extension "inwards" of real world mobility evaluation technique to provide more objective and detailed laboratory studies will meet to form a comprehensive continuum of evaluation techniques as well as a greatly enhanced understanding of the problem of mobility.

REFERENCES

- (1) Kay, L.; "Towards Objective Mobility Evaluations : Some Thoughts on a Theory". A.F.B. Monograph, 1974.
- (2) Elkind, J.I. Forgie, C.D.; "Characteristics of the Human Operator in Simple Manual Control Systems". IEEE Trans Automatic Control, May 1960.
- (3) Gibson, J.A.; "Human Dynamics in Control Situations". Unpublished Report, University of Canterbury.
- (4) Li, Y.T., Young, L.R., Meiry, J.L., "Adaptive Functions of Man in Vehicle Control Systems." Int. Fed. Auto Control Symposium, 1965.
- (5) Vinje, E.W., Pitkin, E.T.; "Human Operator Dynamics for Aural Compensatory Tracking". IEEE Trans. SMC, 1972, 2,4,503-12.
- (6) Gaines, B.R.; "Linear and Nonlinear Models of the Human Controller". Int. J. Man-Machine Studies, 1969, 1, 333-360.
- (7) Hall, I.A.M.; "Study of the Human Pilot as a Servo Element". J. Roy. Aero Soc. June 1963, 351-360.
- (8) Pitkin, E.T. "A Non-Linear Feedback Model for Tracking Studies." Paper presented to 8th annual NASA-Univ Conf on Manual Control, May 1972, Ann Arbor, Michigan.
- (9) Diamantides, N.D.; "A Pilot Analog for Airplane Pitch Control" I.A.S.J., June 1958, 361-370.
- (10) Smith, O.J.M.; "Nonlinear Computations in the Human Controller." IRE Trans BME, 9, 125.
- (11) Fuller, A.T.; "Phase Space in the Theory of Optimum Control". J. Electron Control, 8, 341. (1960)
- (12) Wilde, R.W., Westoff, J.H.; "The Characteristics of the Human Operator Engaged in a Tracking Task." Automatica, 1962, 1,5.
- (13) Mills, A.W. "On the Minimum Audible Angle" J. Acoust. Soc. Am. 1958, 30, 237-246.
- (14) Mills, A.W.; "Lateralization of High Frequency Tones" J. Acoust. Soc. Am., 1960, 32, 132-134.
- (15) Mills, A.W.; "Auditory Localization". In J. Tobias (Ed.), Foundations of Modern Auditory Theory, Academic Press, N.Y., 1972.

CHAPTER 10

CONCLUSIONS10.1 CONTRIBUTION OF THIS THESIS.

The abilities of blind and sighted persons using natural and artificial forms of sensory input to control body movement through the immediate environment have been studied. This thesis therefore helps to fill a serious gap in previous mobility research.

A simple but novel and accurate computer-linked instrumentation system was developed, making it possible to measure locomotor control performance with considerable precision. Performance indices for this purpose had to be defined and validated. While the indices chosen may not prove to be the best possible, they apparently possess at least face validity, and correlate in most cases with the experimenters' subjective visual impressions.

Apart from numerical performance measures, accurate path plots and other graphical data have been obtained. These are informative in themselves and represent an advance over any previous techniques. Combining the several numerical and graphical performance criteria has permitted subtle but important differences in gait and skill to be pinpointed.

These measurement techniques established a framework within which the relative merits of different types of sensory input can be assessed in terms of the degree of locomotor control skill they permit. Datum lines were established for normal visual performance and "random" performance using no auditory or visual sensory input. Between these two extremes the use of artificial aids, degraded

vision, and natural obstacle sense were compared. While these all gave performance above the "random" level, they largely fell short of the "sighted" level. An exception was provided by an experienced Sonicguide practitioner using a simulated version of the device with an enhanced direction cue. His performance in this condition was virtually indistinguishable from the sighted norm, suggesting that even modifications to existing aids could bring about worthwhile improvements.

Measurement of natural obstacle sense performance showed that results could be surprisingly good under optimum conditions - such as shorelining a wall in a quiet environment - but were easily disrupted by changes in ambient sound levels and reductions in "obstacle" size. Small poles appeared to be virtually undetectable, while even large poles allowed only relatively inaccurate locomotor control.

The artificial aids tested - the "Sonicguide" and the "Single Object Sensor" - appeared to facilitate a high degree of locomotor control, equivalent or superior to the use under optimum conditions of the natural obstacle sense. Unlike that sense, however, their efficiency was not dependent on obstacle size, and can (by incorporation of automatic output level controllers) be rendered virtually independent of ambient noise levels.

In the hands of experienced users, both devices gave similar locomotor control performances, falling measurably short of sighted levels. Because of the general similarity of their range and direction cues (both using pitch variation for the former and I.A.D. for the latter) similar levels of locomotor control performance were not unexpected. The differences between these two devices would

probably only become evident when more global aspects of mobility such as landmark recognition were considered, since the Sonicguide is much superior in object identification.

While both devices were inferior in locomotor control facilitation to normal vision, it was shown that by degrading the latter to the extent of removing background information, sighted performance was lowered to a level very close to "experienced Sonicguide user" performance. This illustrated the apparently important role of background information in mobility, but did not necessarily imply that improvements in artificially aided performance could only be obtained by including more background information (which is at present largely excluded in available mobility aid displays).

Techniques were developed for simulating mobility aids with auditory or tactile displays under realistic, mobile conditions. This represented the realisation of an often-mentioned long term goal in the field of blind mobility. The combined simulation and evaluation system was used to assess the effects of variations in auditory display parameters. The complexity of the combined perceptual-motor skills involved in aid use caused difficulties in experiments using naive subjects, but significant changes in performance did occur as range and direction cues were varied. These results were confirmed in experiments using the one available experienced Sonicguide user, whose performance improved considerably when the direction cue was enhanced beyond the manufacturer's specification.

The feasibility of a sonar-driven tactile display for use in mobility was investigated, and several other applications of the monitoring and simulation system have been described.

Consideration of the performance of subjects under a variety of conditions led to the proposal of an elementary model of the mobile human performing a simple locomotor control task. The essential feature of the model is an error detection threshold, which results in subjects wandering off course until the threshold is reached and a correction is made. Variations in performance as sensory cues are varied or removed may be explained in terms of changes in this threshold characteristic. Suggestions are made for evaluating the model parameters.

The relationship between locomotor control and the more general overall problem of mobility has been discussed. It is emphasised that in evaluating sensory aids there is a place for both laboratory and field trials. While the techniques outlined in this thesis are felt to represent a significant advance in objectivity in an important aspect of mobility evaluation, they are intended to complement rather than supplant studies made in the field. Although not providing ready-made solutions, the techniques described are felt to contribute a useful tool for future pure and applied mobility research.

10.2 SUGGESTIONS FOR FUTURE RESEARCH

The broaching of a new area of mobility research has left much ground uncovered. The time spent in establishing suitable measurement techniques and besting their validity resulted in many potential applications being left unexplored or partially explored.

One worthwhile direction of future effort would be the collection of data from a large number of experienced users of different aids, allowing comparisons to be drawn. The lack of suitable subjects encountered during the present research could be overcome

by dismantling the existing monitoring system and reassembling it at a site nearer a centre of blind population. Position data from the system could be logged on a digital tape recorder and analysed off-line.

Experimentation with different tasks and measures should be pursued to extend the present techniques to more realistic outdoor-type situations, possibly with the inclusion of other pedestrians.

Suitable refinement of the instrumentation system should permit more sophisticated models to be proposed and evaluated, enhancing general understanding of blind mobility.

With new generations of computers, the simulation techniques described here could be considerably extended, since computing speed would be less of a limitation. It is felt that simulation techniques are most likely to yield satisfactory results if subjects experienced in the use of aids broadly similar to those simulated are used. Alternatively, considerable time should be spent in training each subject. This requirement would probably necessitate a dedicated computer.

10.3 OVERALL CONCLUSIONS.

As a result of this research, the means are now available to perform a direct comparison between several different aids, in terms of their ability to assist accurate control of bodily path through the environment. The objective data thus obtained could be used in conjunction with the results of field trials in forming overall conclusions.

Results to date indicate that while present aids are still inferior to normal vision in terms of locomotor control, they show

APPENDIX 1

TRAINING METHODS

1. HYBRID COMPUTER SIMULATION SYSTEM (chapter 3),

Appearing below is a copy of the instructions given to subjects before testing began. Example given is for the "chair" apparatus.

TRAINING INFORMATION FOR COMPUTER SIMULATION.

This computer system is designed to test types of sensory aid which use sound as their means of delivering information about the environment to the blind person.

The computer presents an imaginary environment consisting of a long row of poles spaced 4 metres apart, and your task is to 'walk' down the centre of the path, parallel to the row of poles (fig.1).

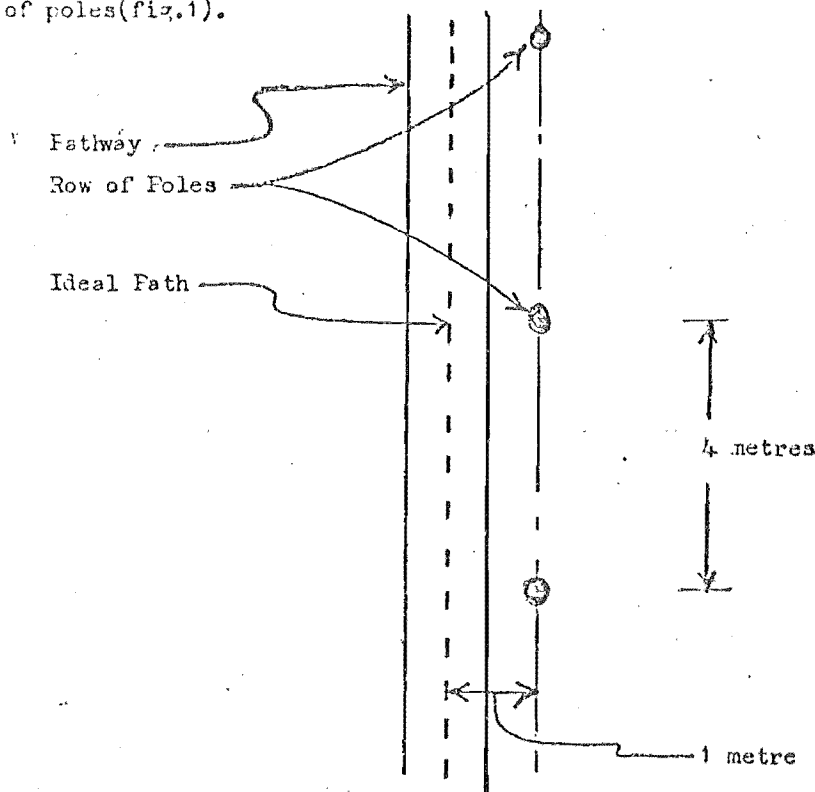


Fig.1. The Task.

In addition, the computer does the job of the blind-aid by feeding appropriate audible signals to your earphones. The signal you receive from the blind-aid will depend on where you move to in the (imaginary) environment and where you are 'looking' (i.e. which way your head is pointing).

To move around in this (imaginary) environment, you align your body (i.e. the seat of the chair) in the direction in which you wish to move, and press the hand-held switch. This results in a step of length 2 feet.

You may 'look' in any direction by simply moving your head. It is important to remember, however, that the steps are taken in the direction the body is pointing in, and are not affected by head movement.

The particular blind-aid being simulated in this case has a range of about 6 metres, and any pole within this distance from you and within an arc of about 60 degrees of in front of your head will be within range of your blind-aid.

With reference to fig.2, objects within the shaded region will be in range, and will produce an audible signal on the blind-aid. There will never be more than 2 objects in range at any given time.

The signal corresponding to each object will have a frequency or 'pitch' proportional to the distance from your head to the object. As you approach an object, the signal you hear will steadily decrease in pitch.

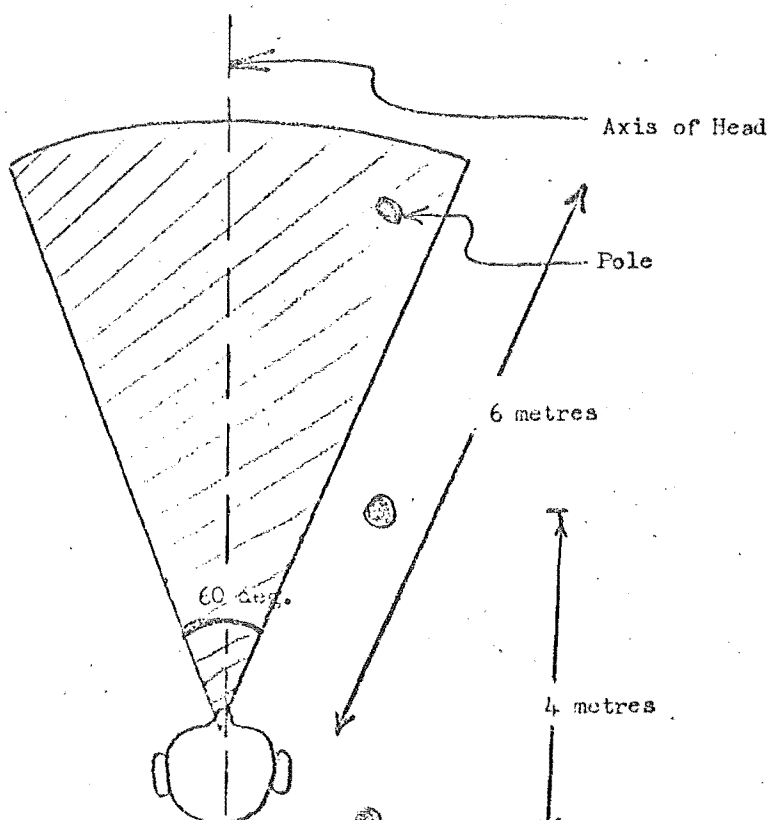


Fig.2. Range of Sensory Aid.

An object off to one side of your head will produce a signal which is louder in one ear than in the other-- so the sound will seem to be coming from a particular spatial direction (i.e. the direction of the object). Thus an object to the right of your head will produce a signal which is louder in your right ear than in your left.

As you move towards an object the pitch of the signal will change in discrete 'jumps' each time you take a step, rather than changing gradually.

In each experimental run, you will take 100 steps along the path and the computer will calculate your performance.

2. DIRECTION CUE VARIATION EXPERIMENT (chapter 6).

The following procedure was followed for the ten training trials referred to in section 6.3:2.

Trials 1, 2, and 3: Instructor guided subject along correct path.

Trial 4: Subject left to himself for one trial.

Trial 5: Instructor guided subject deliberately too close to, and too far away from, the shoreline, to show effects of deviating off course.

Trial 6: Subject attempted to repeat (5) by himself.

Trial 7: Instructor guided subject along correct path.

Trials 8, 9, and 10: Subject performed these trials by himself.

Instructor gave verbal guidance as necessary.

In this program, emphasis was placed on giving the subject a good understanding of the device cues and the signals he would receive if he deviated from the correct path, together with raising his speed to a reasonable level (at least 0.8 m/sec) during the latter half of the program.

APPENDIX 2

PROGRAMMING FOR FLEXIBILITY OF DIRECTION CUE SPECIFICATION

A method of programming whereby I.A.D., beamwidth, and loudness roll-off can each be independently specified is briefly described below.

Let I_L , I_R be signal amplitudes in the left and right auditory channels. Assume an arrangement of one transmitting transducer and two receivers, the latter splayed α degrees away from the transmitter. Assuming ideal polar response characteristics, the received amplitude in the left channel can be written as:

$$\begin{aligned}
 I_L &= I_{\text{transmitted}} C \exp \left(-\frac{(\theta + \alpha)^2}{K} \right) \\
 &= C \exp \left(-\frac{2\theta - \alpha^2}{KT} \right)
 \end{aligned}
 \quad A1.$$

I_R can be found similarly, giving an inter-aural amplitude ratio of:

$$\frac{I_L}{I_R} = \exp \frac{8\alpha\theta}{K^2} \quad A2$$

Thus the I.A.D. is dependent on the factor 1 (which determines the beamwidth) as well as on . To avoid this difficulty, I_L and I_R can be written as:

$$I_L = \exp - (a\theta^2 - b\theta + c) \quad A3$$

$$I_R = \exp - (a\theta^2 + b\theta + c) \quad A4$$

where the constant C is expressed as $\exp(-c)$, and the I.A.D. is now:

$$\frac{I_L}{I_R} = e^{2b\theta} \quad A5$$

and depends solely on the value of b . In computation, b can be calculated from the desired I.A.D. in dB/degree, viz:

$$b = (\text{dB/degree}) \cdot \frac{9}{2\pi \log e} \quad A6.$$

For the purposes of computation, c can be set to zero and it remains to choose a .

Let the desired half beamwidth be B , and the desired roll-off between the maximum point in each channel and the edge of the beam be $R0$ decibels.

It can be shown that

$$a = 2\epsilon bB + 2\gamma bB + \gamma^2 \quad A7$$

$$\text{where } \gamma = \frac{RO}{20 \log_{10} e}. \quad A8.$$

Thus in computing the required amplitudes in each channel, the formulae A3 and A4 are used. The values of a and b are calculated by the program from the required values of I.A.D., B, and RO, which are entered via teletype.

APPENDIX 3

A PROPOSAL FOR A SONAR-DRIVEN TACTILE DISPLAY.

An experimental mechanically-scanned sonar system for use with a tactile imaging system is illustrated in Figure 1. A brief description only is given here.

In the illustrated design, an FM sonar with a narrow beam rotating receiver is used. The schematic shows that a bank of filters is used to extract range information. The bandwidths of these filters and Doppler effects occurring at the outside edges of the receiver at limits to the maximum scanning rate - approximately 5 - 10 Hz being envisaged.

To interface the sonar with an existing 32 x 32 element tactile display, the auxiliary circuitry shown in block diagram form would be needed. Because of the difficulty of accurate scanner speed control, it is necessary to synchronise the tactile display circuitry using pulses from the rotating scanner. This means, in effect, disconnecting the internal clock of the tactile display and driving its raster scanning circuitry externally. With reference to the figure, the tactile display

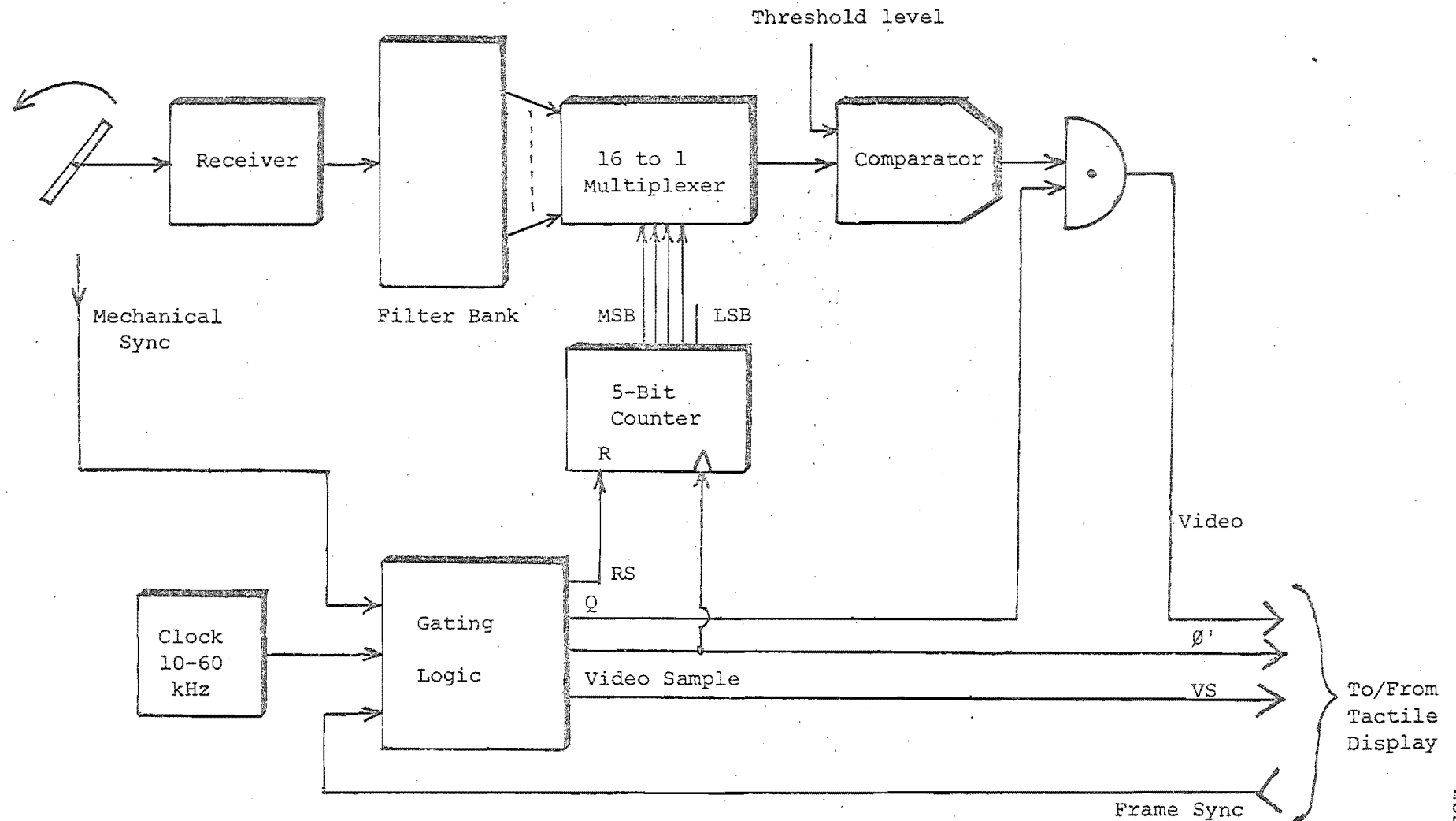


Figure 1.
Possible Experimental Sonar-Driven Tactile Display

is arranged so that the fast scan occurs along the "range" axis of the display, and the slow scan occurs along the horizontal "azimuth" axis. This results in distant objects appearing towards the lower abdomen and nearer objects towards the top, while objects to the right and left of the subject will appear on the corresponding sides of his abdomen. The system clock drives a 5-bit counter which causes a multiplexer to scan rapidly through the 16 range element (filter and detector outputs). The output of this multiplexer, processed by a threshold detector and a variable gain block forms the video input signal to the tactile display.

APPENDIX 4

PUBLICATIONS

The following papers were published or prepared in the course of this research.

Strelow, E.R.; Brabyn, J.A., Clark, G.R.S.; "Apparatus for Measuring and Recording Path, Velocity, and Direction Characteristics of Human Locomotion" Behaviour Research Methods and Instrumentation, 1976, 8, 5, 442-446.

Brabyn, J.A., Strelow, E.R.; "Computer-Analyzed Measures of Characteristics of Human Locomotion and Mobility". Behaviour Research Methods and Instrumentation, 1977, 9, 456-462.

Kay, L., Bui, S.T., Brabyn, J.A., Strelow, E.R.; "Single Object Sensor: A Simplified Binaural Mobility Aid". Journal of Visual Impairment and Blindness, May 1977, 210-213.

Gregson, R.A.M., Smith, D.A.R., Strelow, E.R., Brabyn, J.A.; "Acute Effects of Alcohol on Measures of Walking Performance". Applied Psychological Measurement, In Press.

Brabyn, J.A., Sirisena, H.R., Clark, G.R.S.; "Instrumentation System for Blind Mobility Aid Simulation and Evaluation". IEEE Trans on Biomedical Engineering, Accepted subject to revision.

Brabyn, J.A., Kay, L., Strelow, E.R.,; "Effects of Simulated Cue Variations on an Experienced Sonic-guide User". Paper presented at Psychological Society Meeting, Oxford, May 1977.

Brabyn, J.A., Strelow, E.R.,; "Locomotor Control Study of a Long-Term Sonicguide User". In Preparation.